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PRODUCTION OF RADIOACTIVE ION BEAM BY ECRIS

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1 Introduction

During the past few years, world-wide interest has developed in the use of radioactive ion beams (RIB) for the research of nuclear reaction, nuclear structure and astrophysics. As a consequence, many RIB facilities have been proposed and constructed over the world[1]. One of the most important tasks in those RIB facilities is to develop a reliable, long-lived and efficient ISOL ion source with fast release properties, which have been included in the reviews by Ravn[2], Van Duppen[3] and Alton[4]. For radioactive ion beam production, the ion source should ideally exhibit the following properties: high efficiency; short delay time; stable operation; long life time; high temperature operation in order to minimize the diffusion time from the target and residence time on the surface; low energy spreads; chemical selectivity; flexibility for adaptation to different temperature ranges and modes of operation; target temperature control; stable electrical and mechanical properties[4]. One of the most exciting development of ISOL ion source in the last few years is the use of electron cyclotron resonance ion sources (ECRIS). It has turned out that ECRIS has very high ionization efficiency for the generation of ions from nitrogen to noble gases. The trend of using ECRIS to produce radioactive ions seems to be increasing. Up to now, so many ECR ion sources have been put into operation for the production of radioactive ion beams. The prototype on-line ECR ion source was first developed in Karlsruhe for ISOL applications[5], and then in TRIUMF[6], Louvain-la-Neuve[7,8], PSI[9], Grenoble[10], GANIL[11] and so on. we outline the characteristics of ECR ion sources for radioactive ion beam generation. Particular emphases have been put on the ECRIS ionization efficiencies and the design aspects for RIB production. Finally, two compact ECR ion sources proposed for RIB production in FLNR are introduced.

2 Concept and Features of ECRIS in RIB Production

The production of radioactive ion beam is achieved by the bombardment of target material of sufficient thickness to stop the nuclear-reaction products. The concept and steps for the radioactive ion beam production by ECR ion source is shown in Fig.1. The thermalized nuclear-reaction products are continuously transferred from the target to the ion source , and ionized by the hot electrons in ECR plasma, and finally extracted by a high voltage in order to be mass-analyzed by means of a magnet. The radioactive beam intensity is determined by [12]

$$I = \sigma \phi N \epsilon_1 \epsilon_2 \epsilon_3 \quad (1)$$

where σ is the formation cross sections for the interest nuclear reactions , ϕ is the primary beam intensity, N is the target thickness and the resulting power density, ϵ_1 is the product release and transfer efficiency, ϵ_2 is the ion source efficiency, ϵ_3 is the delay transfer efficiency.

The general problem is to separate the 10^{-1} to 10^{12} produced nuclei(per second) from the 10^{23} target atoms and to transfer them to the ion source. The main losses are due to release loss, decay loss and condensation on the transfer tube and the chamber wall of ECR ion source.

ECR ion sources at present seem to be the most promising way of making further progress to the radioactive ion production. That is because of the following important features [3,4]:

(1). The absence of hot cathode and good confinement to ions and hot electrons make ECRIS have desirable characteristics including good long-term stability, long life time reliability, and ease of operation.

(2). High electron density and high electron temperature result in a higher ionization efficiency.

(3). Excellent capability for efficient production of multiply charged ions.

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(4). Particularly, good performance for the processing of highly volatile or gaseous materials.

(5). The ion confinement reduces the wall collision rates. This could decrease the effusion time by reducing the losses due to condensation of nonvolatile atoms on the wall of the chamber.

(6). ECR ion sources dot not show any elemental selectivity

The principal disadvantage of ECR ion sources for RIB production is that, in its present state of development, the relatively low temperature of chamber wall severely limits the number of species that the sources can be processed, since the wall temperature is so low that atoms condensed on the wall remain there for a long time.

3 Ionization Efficiency of ECR Ion Sources

Ionization efficiency of ECRIS is usually defined as the ratio between the number of charged ions extracted from the source and the number of atoms injected into the source. Losses due to radioactive delay during the thermolization, transport and ionization process are not taken into account[3]. Generally, radioactive elements are produced in very small amounts, in order to transform them into ions, the ionization efficiency of ion sources must as high as possible. The performance of an ECR ion source for a radioactive element is the same as for a stable one. The ionization efficiency can be assumed to be the same for stable and radioactive element because the ion confinement time in an ECR ion source is much smaller than the lifetime of the radioactive element.

The ionization efficiency of an ECR ion source depends on a set of plasma parameters, such as the plasma density , the neutral density, the ion temperature, the electron temperature, the plasma potential and the confinement time. The change of all these internal variables results from the external variables of ECRIS, such as magnetic configuration, magnetic strength , microwave frequency and power, microwave coupling efficiency, plasma chamber dimensions, gas pressure and gas mixing effect, source pumping and source extraction system .

Table 1. Maximum ionization efficiencies for neon from the three ECRIS

Q	Karlsruhe ECRIS	Leuven ECRIS	GANIL NANOGAN
1+	30 %	52 %	25 %
2+	1.5 %	26 %	7.5 %
3+	0.05 %	16 %	.4 %

Table 2. Main parameters of the three ECR ion sources

Typical Parameters	Karlsruhe ECRIS	Leuven ECRIS	GANIL NANOGAN
structure	coils+hex.	coils+hex.	mag.+octu.
ω_{rf} (GHz)	6.4	6.0	10
B_{ECR} (T)	0.229	0.214	0.36
R	2.0	1.4	2.8
L_m (mm)	200	300	150
B_{zmax} (T)		0.28	0.75
B_{rmax} (T)	0.3	0.4	0.6
ϕ (mm)		55	26
V (KV)	40	10	15
d (mm)	$1 \sim 10$	$1 \sim 10$	5
P_{rf} (W)	800	200	50

(ω_{rf} microwave frequency, B_{ECR} resonance field , R mirror ratio, L_m mirror to mirror length of the axial magnetic field, B_{rmax} maximum field on the pole of multipolar permanent magnet, B_{zmax} the peak of axial magnetic field, ϕ plasma chamber diameter, V typical extraction voltage, d exit hole of the plasma electrode, P_{rf} typical microwave power.)

The ECRIS ionization efficiency is high compared with conventional ion sources. This is because the plasma density is generally much higher than the neutral density in the plasma . Moreover, the better the confinement, the higher are the ionization and electron heating efficiencies, and the longer are the ion and electron lifetimes. This results in an efficient multiply charged ion production in ECRIS.

It is difficult to say which parameters are dominant in determining ionization efficiency, since all of those parameters are related one another. We compared the maximum ionization efficiencies of different charge states for Neon, obtained from three different ECR ion sources, Karlsruhe ECRIS[5], Leuven ECRIS[7,8,13] and GANIL NANOGAN[11], Shown in Table 1. The main parameters of these three ECR ion sources are compared in Table 2. It is important to underline that 40 – 50% efficiency for Xe^+ was got by a 2.45GHz ECRIS at the SARA online separator in Grenoble[11]. This source has no radial multipolar magnet, and only for single ion production. All these evidence shows that ECRIS ionization efficiency does depend on the optimum design and compromise among those external variables of the source.

Particularly, ECR ion sources have a higher ionization efficiency in the production of multiply charged ions. Table 3 shows the maximum ionization efficiencies of different elements with multicharged ions in optical conditions , produced by Karlsruhe ECRIS[5] and Leuven ECRIS[7,8,13]. Meanwhile, we note for Argon ionization efficiencies of around 25% and 20% were measured respectively for the 8+ and 9+ charge states by GANIL ECRIS [3]. Judged from the stable metal consumption of accelerator ECRIS, ionization efficiencies of moderately volatile elements such as C_a in a given high charge states seems to be of the order 1% [12].

The ionization efficiencies of neon isotopes ^{18}Ne, ^{19}Ne and ^{20}Ne with different charge states were measured in GANIL ECR3 [14], as shown in Fig.2. We can see from Fig.2 that the difference of ionization efficiency for different neon isotopes is not so large.

For an ECR ion source already put into operation, the ionization efficiency is determined by axial magnetic field configuration, rf power, gas pressure, and support gas . They are analyzed in detail as following:

Axial Magnetic Field Configuration: Optimum performance of an ECR ion source is due to axial magnetic field configuration, because the axial magnetic field configuration not only determined the plasma conditions but also the extraction optics, and thus the ionization efficiency. In the performance of an ECR ion source, we have to tune the coil currents to optimize the magnetic field configuration so as to make the ionization efficiency as high as possible.

RF Power: From the previous experiments performed in Karl-

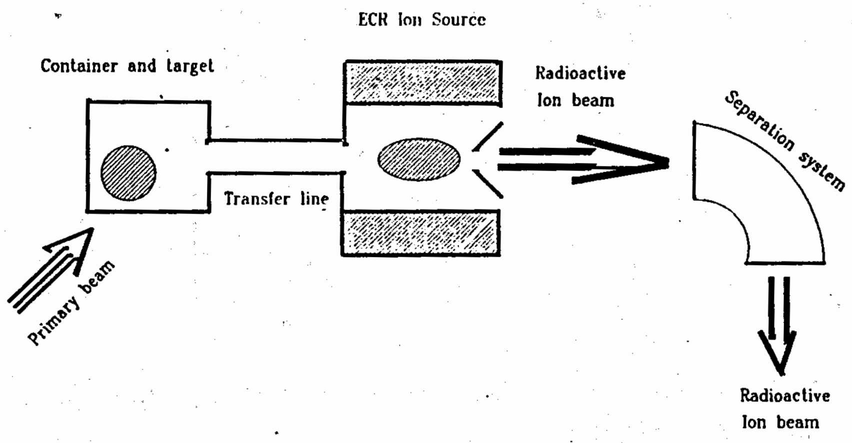

Fig.1 The concept and steps for RIB production by ECR ion source.

Table 3. Maximum Ionization Efficiency of Different Elements with Multicharged Ions from the two ECR Ion Sources

Element	Charge State	Karlsruhe ECRIS	Leuven ECRIS
C	1+	10.0%	15%
	2+	0.7%	
	3+	0.01%	
N	1+	26%	20%
	2+	1.7%	6%
	3+	0.03%	4%
N_e	1+	30%	52%
	2+	1.5%	26%
	3+	0.05%	16%
O	1+	53%	
	2+	1.7%	
	3+	0.03%	
A_r	1+		40%
	2+		20%
	3+		7%
Xe	1+	65%	90%
	2+	8%	20%
	3+	0.5%	
	4+		7%

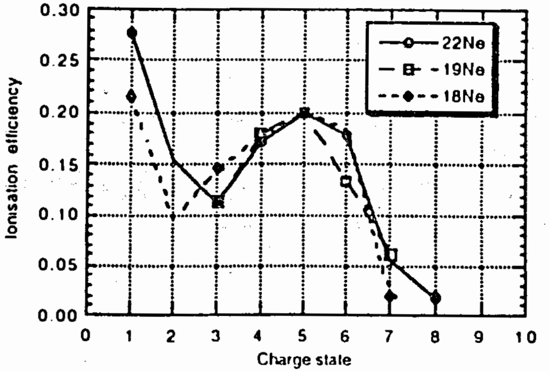

Fig.2 Ionization efficiencies with different charge states for neon isotopes (from Ref.[14])

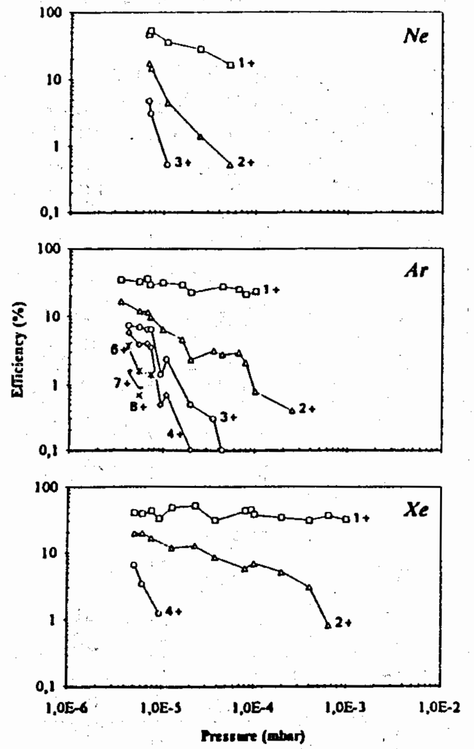

Fig.3 Dependence of ionization efficiencies on the source pressure for the noble gases (from Ref.[13])

sruhe[5], PSI[9], and Leuven[8], it seems that a variation of the microwave power does not change the ionization efficiency for single charged ions. Those experiments indicated that low rf power(50-200 W) was sufficient to obtain the maximum ionization efficiency for single charged ions. The reason for this phenomenon probably lies in the fact that the ionization rate for single charged ions is kept almost constant when rf power is increased. The electron energy might be easy to be raised above the ionization threshold for single charged ions(usually very low, for A_r^+, only $60-70ev$) by increase of rf power, which results in decrease of ionization cross section. The product of ionization cross section and electron velocity (σv_e) is, however, quite constant for this energy, and thus the ionization rate and efficiency stay constant[10]. Unfortunately, there has been no detailed measurements available for the ionization efficiency of multiply charged ions versus rf power.

Gas Pressure : The ECRIS ionization efficiency is sensitive to the gas pressure , since the gas pressure is related to the neutral density, the electron density and ion density in the plasma. Measurements of the ionization efficiencies from several ECR sources [5,6,9,13] showed a strong dependence on the gas pressure, as shown in Fig.3 [13]. Lower source pressure results in higher ionization efficiencies and this effect is stronger for higher charge states. We can find from Fig.3 that this dependence seems to decrease for the higher masses, especially for the lower charge states, even disappear for single charge state [13]. This can be explained in a qualitative way by means of charge exchange between the support gas atoms and the ions of the main gas, the main gas atoms and the ions of the main gas. The higher the gas pressure, the higher neutral density inside the plasma, and then the higher charge exchange rate. Moreover, the charge exchange cross sections vary with $I^{1.17}$ (I is the charge state). As we know, higher charge exchange rate causes a lower ionization efficiency.

Support Gas : Many groups have tested different support gases to increase the efficiency [5,6,9,13]. It seems that Helium and Hydrogen are the good support gases for N_2 and noble gases. The mechanism of such gas mixing has not been understood very well although it is clear that support gas does raise the ionization efficiency for single charge state. The effect of support gas on the ionization efficiencies of high charge states has not been studied in detail. The Leuven group [8] proposed that charge neutralization due to charge exchange between the ions of main gas and the neutral support gas might play an important role in such gas mixing mechanism. They pointed out the ionization efficiency would be higher at the same neutral density for support gases having a higher ionization potential. But there has been no report that Neon could be a good support gas since the ionization potential of Neon is similar to that of Helium. Whether the effect of support gas on the ionization efficiency has the same mechanism as the gas mixing effect on the ion currents of high charge states in ECRIS is still a open question.

4 Design Aspects of an Efficient ECR Ion Source for RIB Production

The performance of an efficient ECR ion source depends quite on a optimum design:

(1). We have to get a good compromise among rf frequency, magnetic configuration, dimensions of plasma chamber, and the possible financial support according to the purpose of the source.

(2). In view of the diffusion and release of radioactive ions inside the source, we have to make the source very compact in order to minimize the distance between a thick production target and the ionization area.

(3). we have to adapt the cooling system of the source to the temperature of the target and its transfer line.

(4). The plasma chamber should be designed to avoid the condensation of the charge material on the wall, meanwhile, to keep the temperature of radial multipole permanent magnet not very high.

(5). To optimize the extraction conditions so as to get a fast extraction to the interest ions , which is important for the short-lived radioactive ions.

(6). To adapt the technological structure of the source to the very radioactive environment in order to be able to handle the source automatically[11].

5 Two Compact ECR Ion Sources for RIB Production in FLNR

In Flerov Laboratory of Nuclear Reaction, two compact ECR ion sources for radioactive ion beam production have been proposed, so-called DECRIS-10 [16] and DECRIS-2.45 . DECRIS-2.45 is already under construction.

DECRIS-10 is a compact 10 GHz ECR ion source equipped with a new hexapole with continuous easy axis orientation. This source is dedicated to the high charge states and high ion currents. Its structure is shown in Fig.4. Because of this new hexapole, this source has many interesting characteristics, such as simple, flexible and compact structure (only 34 cm in length); the new hexapole with thickness only 25 mm, radial field on the wall 0.8 T; lower electric power consumption (40 KW) ; lower cooling water pressure (4 atm); higher axial magnetic field peak (1.2 T) and so on. It is possible to couple this source directly with an on line target system for ionization of radioactive atoms, or put it on a high voltage platform.

DECRIS-2.45 is a compact 2.45 GHz ECR ion source consisted of whole permanent magnets. It is particularly used for the metal radioactive ion production with low charge states and low ion currents($Q \leq 3$, $I \leq 10^{12}$ pps). The source body is only 15 cm in length and 16 cm in diameter. The axial magnetic field is provided by two permanent magnets(SmCo). The peak of the axial magnetic field is 0.18 T. The Hexapole is constructed by 18 pieces of small SmCo permanent magnets. The radial field on the wall is 0.22 T. To avoid the condensation of the charge material on the plasma chamber wall, a quartz tube will be used as plasma chamber. Four turns spiral antenna is wound around the quartz tube for rf couple. The structure is shown in Fig.5 .

6 Conclusion

The applications of ECR ion sources in the production of radioactive ions have been becoming more and more interesting because of

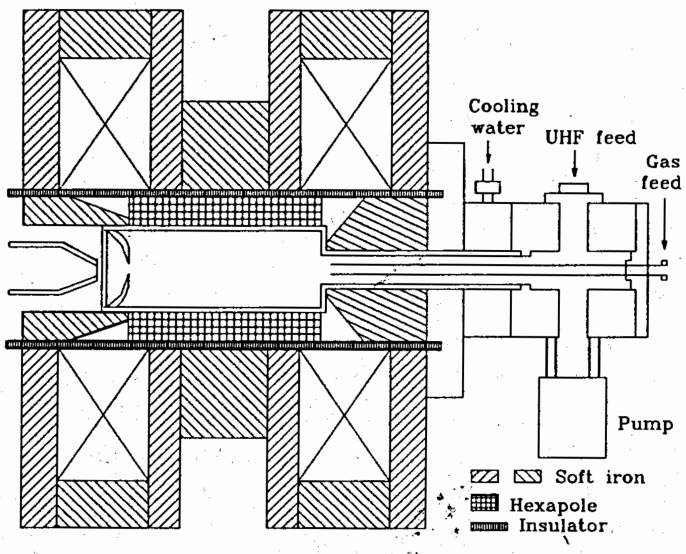

Fig.4 Structure of a compact 10 GHz ECRIS for RIB production

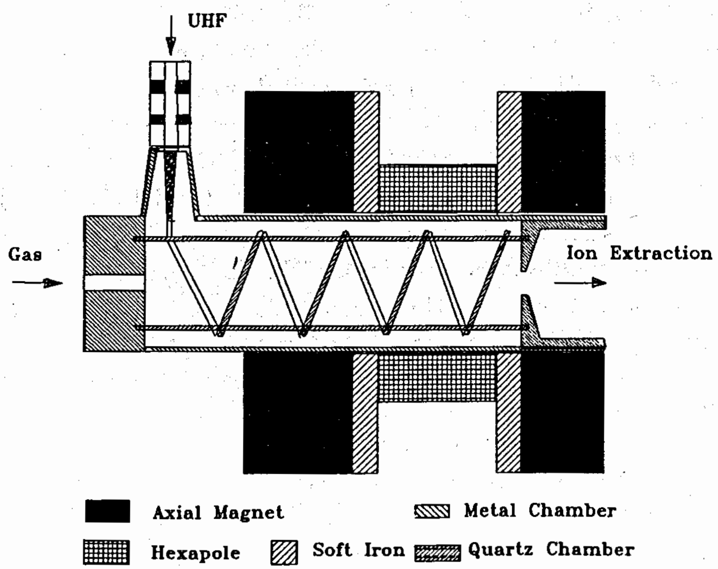

Fig.5 Structure of a compact 2.45 GHz ECRIS for RIB production

obvious advantage over the conventional sources in terms of ionization efficiency. The efficiency of an ECR ion source is determined by various parameters of the source which have been analyzed in the paper. Generally speaking, ECR ion sources can achieve the ionization efficiency as following:

For single charge state of gaseous element, 10% – 90%

For middle and high charge state of gaseous element, ~ 20%

For metal ions with high charge state, a few percent.

The efficient performance of an ECR ion source depends on optimum design and a good compromise between magnetic field configuration (field shape and strength), rf system (frequency, power and coupling) and the plasma volume. In present state of ECRIS development, the species for ISOL applications are limited only in gases. It seems that much more efforts should be made in the development of metallic radioactive ion production by ECRIS. It is still a more or less open question that whether high efficiency and very high delay time could be obtained for the production of those metallic radioactive ions by ECRIS . Only dedicated reseach and development work in this field will give us the answer.

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Кутнер В.Б., Ефремов А.А., Чжао Хунвей E9-95-113
Получение радиоактивных пучков в источнике ионов типа ECRIS

В работе представлен обзор ЭЦР — источников ионов, используемых для получения радиоактивных пучков. Коротко описываются характерные черты ЭЦР–источников. Проведен анализ ЭЦР — источников с точки зрения ионизационной эффективности и конструктивных особенностей. Сравнение ионизационной эффективности разных ЭЦР — источников показывает, что ионизационная эффективность зависит от компромисса между различными параметрами работы ЭЦР — источника и его оптимальной конструкцией. Представлены конструкции двух компактных ЭЦР — источников ионов (10 ГГц и 2,45 ГГц) для получения радиоактивных пучков, предложенных к реализации в Лаборатории ядерных реакций им.Г.Н.Флерова.

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Kutner V.B., Efremov A.A., Zhao H.W. E9-95-113
Production of Radioactive Ion Beam by ECRIS

A review on the production of radioactive ion beam by ECR ion sources (ECRIS) is presented in this paper. The ECRIS features used for the radioactive ion production are described briefly. Particular emphases have been put on the analysis of ECRIS ionization efficiencies and the design aspects for radioactive ion beam production. A comparison of the ionization efficiencies for multiply charged ions from the different ECR ion sources is presented, which shows that the ionization efficiency of an ECR ion source does depend on the compromise between various ECRIS parameters and the optimum design to the source. Finally, two compact ECR ion sources proposed for radioactive ion beam production in FLNR are introduced in brief.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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