SOME ASPECTS OF CHARGE EXCHANGE IN THE COOLER DESIGNED FOR I.V.KURCHATOV INSTITUTE OF ATOMIC ENERGY

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Abstract: The paper presents the calculation results of ion charge exchange for lithium, boron, nitrogen, and neon in nitrogen and carbon for 1-200 MeV/nucleon energies. These results have been used for estimation of the lifetimes of beam in interaction with the internal target during the experiment, for estimation of losses from collisions with molecules of the residual gas in acceleration, and for choice of the thickness for the stripper in charge exchange injection for the cooler being designed for IAE.

I. Introduction

The I.V.Kurchatov Institute of Atomic Energy in collaboration with the Nuclear Physics Institute (Novosibirsk) are engaged in development of a cooler/1/with the injector-cyclotron being operated at IAE /2/The parameters of the external beam of the cyclotron, such as energy, charge, pulse current of about 1 ms duration, microbunch intensity with a duration of several ns shown in Table I, are sufficient for use of charge exchange injection which is simple enough for application in practice and enables the acceptance of the storage ring to be reduced, thus providing high liminosity under certain conditions.

Table 1 - Parameters of the external ion beam of the IAE cyclotron

Ion	$^{6}Li^{2+}$	$^{7}Li^{2+}$	$^{12}C^{4+}$	$^{14}N^{5+}$	$^{16}O^{5+}$	$^{20}Ne^{5+}$
E/A, $\frac{MeV}{nucl}$	6.5	4.1	6.5	8.2	6.2	3.8
I_{pulse}, A	100	100	100	30	20	10
$n_b \times 10^{-6}$	30	15	15	4	3	0.5

One of the main reasons for beam losses is charge exchange in the stripper material in injection on the residual gas molecules in acceleration and on the internal target molecules in the experiment. The latter process reduces the lower energy of the nuclei accumulated, which may be used for experiments with the internal target. The beam lifetime can be increased using the multicharge work where the dispersion function and its derivative is close to zero. But then the aperture of the storage ring must be appreciably increased, particularly, in work with light ions of the lithium-type for which the relative change in the charge is large. Therefore this way is not suitable for the IAE cooler. It is important to calculate the optimal thickness of the stripper. On the one hand, it must be sufficient for stripping the largest part of ions injected out of the cyclotron, on the other hand, it must be as little as possible so that the emittance of the beam accumulated during the injection be not increased.

2. Calculation of charge exchange cross sections

Calculations of the cross sections of loss of electron loss by hydrogen-like ions for the case of ion collision with gaseous nitrogen were carried out in the Born approximation (PWBA). The nitrogen has been chosen as the most probable component of the residual gas. Besides there are experimental data on it, which can be used for comparison with the calculation. The analysis of the possibility for using the Born approximation in calculations of the cross sections of one-electron particle ionization has revealed that this approximation is valid in the velocity range $2Z_tV_o$ (where $Z_t=7$ is the nuclear charge of medium atoms). The difference between the experimental cross sections obtained in the molecular nitrogen and the calculation results for the atomic target does not exceed 20%.

In the limiting case of high velocities $v > 3zV_0$ the expression for cross sections $\sigma_{z-1,z}$, has the form:

$$\sigma_{z-1,z} = 4\pi a_0^2 \frac{1}{z^2 (\frac{v}{v_0})^2} \left\{ Z_t^2 \left(1+0.56 \ln \frac{z}{2Z_t}\right) + Z_t \left(1+0.56 \ln \frac{z}{2Z_t}\right) \right\} \quad (1)$$

Fig.1 presents the values of $\sigma_{z-1,z}$ for Li^{2+}, B^{4+}, N^{6+} and Ne^{9+} ions in N_2 depending on the ion energy E. For lithium ions, the cross sections $\sigma_{2,3}$ decrease, in accordance with (1), with increasing E as E^{-1} while for the neon ions $\sigma_{9,10}$ in the region E=2-10MeV/n depends weakly on E and only beginning from E > 20MeV/n $\sigma_{9,10}$ are described by formula (1). The experimental data available for Li^{2+} and N^{6+} ions from /3,4/ agree well with the calculation results.

As follows from the comparison of the experimental results the cross sections of electron loss by hydrogen-like ions in gaseous carbon are lower by about 25% than in nitrogen for the 3 MeV/n C^{5+} ions considered in /3,5/. The similar value of reduction in the $\sigma_{z-1,z}$ cross sections in carbon as compared with nitrogen also follows from (1).

Considering the process of fast ion charge exchange in the medium it should be born in mind two main mechanisms of electron capture by ions. In the velocity region $V < 10^{10}$ cm/s ($E < 10^2$ keV/n) electron capture occurs due to the Coulomb interaction between the fast ion (nucleus) and the medium atom. The basic regularities of the electron capture cross section are described qualitatively correctly in the simplest quantum mechanics Oppenheimer-Brinkman-Kramers (OBK) approximation /6/ in which the interaction of incident particle with medium atom electrons are only taken into account. The cross section $\sigma_{z,z-1}$ changes with the increasing ion velocity $\sigma_{z,z-1} \sim \frac{z^5 Z_t^5}{v^{12}}$ (or $\sim v^{-11}$)
However in this nearly relativistic region of velocities the process of radiation electron capture (the process reverse to the photoeffect) is more essential. The electron capture cross section decreases with increasing v

much more weakly and proportionally to the number of electrons in the medium atom, i.e. is proportional to Z_t.

The analysis of the experimental data has revealed that in the light media (Z_t=4-7) the radiation capture will dominate in the region $V > 10^{10}$cm/s (i.e. at $E > 10^2$MeV/n).

The calculations of cross sections in nitrogen were based on the binding between the cross sections $\sigma_{z,z-1}$ for the nuclei and the cross sections $\sigma'_{1,0}(H^+)$ for protons in the same medium, found experimentally and theoretically /7/.

$$\sigma_{z,z-1} = \sigma_{1,0}(H^+) \begin{cases} z^2\left(\frac{v}{zv_0}\right)^3 & z \geq \frac{v}{zv_0} \\ z^5 & z \leq \frac{v}{zv_0} \end{cases} \qquad (2)$$

Fig.2 presents the cross sections for Li^{3+}, B^{5+}, N^{7+} and Ne^{10} in N_2 depending on E. In accordance with (2) relatively light nuclei (Li, B) capture the electron into the ground state 1s and $\sigma_{z,z-1} \sim z^5$ while heavier nuclei (N,Ne) - into the excited state, i.e. $\sigma_{z,z-1} \sim z^2$. The experimental data for nitrigen nuclei N^{7+} in celluloid /8/ and nitrogen /4/ agree well with the calculation results.

3. Beam losses because of charge exchange by the residual gas

Solving the differential equation of ion losses in the process of acceleration and the experiment with the internal target because of charge exchange by the residual gas molecules (assuming that its basis is N_2) the expression for the fraction of lost ions can be obtained:

$$\frac{\Delta N}{N} = 1 - \exp\left[-(2.1\cdot10^{-27}\int_0^t P\beta\sigma_{at}\,dt)\right]$$

where P is the pressure, torr; $\beta = \frac{v}{c}$, σ_{at} is the total charge exchange cross section i.e. the sum of the cross sections of electron loss and capture, cm^2/s, t is the time, s.

The calculations carried out taking into account the dependences shown in Figs.1 and 2 for the chosen mode of ion acceleration in the cooler for a time of 1s, internal target experiment time 1s and residual gas pressure 10^{-9}torr /1/ have shown that the chosen method of charge exchange injection these losses are negligible (< 1%). If not charge exchange injection had been chosen and ions having the charge they had in the cyclotron were accelerated, the losses would have been too large.

4. Beam lifetime because of charge exchange by the internal target molecules

In the cooler designs it is often planned to perform physical experiments with the internal target within a wide range of energies of ions accumulated. The charge exchange cross section increases strongly with decrease in the ion energy, therefore, on a significant energy reduction losses may reach an inadmissible value. As an illustration Fig.3 presents the lifetimes of different nuclei (Li, B, N, and Ne) in the IAE cooler in interaction with the nitrogen target where the atom density is 10^{14}atom/cm^2, calculated using the data of Fig.1. (by the lifetime the time, at which the beam intensity reduces by e times, is meant). It is seen from Fig.3 that the lowest energy for neon nuclei is 20 MeV/n, for nitrogen - 15 MeV/n, boron - 10 MeV/n and lithium 5 MeV/n. With increase in Z_{target} the charge exchange cross section increases for the above energies of the nuclei more than proportionally to the number of the medium element and, hence, the value of the lowest energy admissible for the experiment increases. For example, in the case of the lead target ($Z_{Pb}/Z_N \simeq 12$) for the above mentioned nuclei the minimum energies have to be increased more than by a factor of 2. Otherwise the beam intensity will be essentially lower (more than by an order of magnetude).

5. Calculation of the equilibrium stripper thickness

The stripper is supposed to be made of carbon film. The main feature of the solid strippers is a high medium density ($\sim 10^{23}$ atom/cm^2). Therefore the excited ions produced as a result of electron capture and excitation are not allowed to relax into the ground state by emitting photons or Auger electrons. This means that for the ion beam to be in equilibrium upon its passing through the solid target the equilibrium both in charges and in excited states has to be established /9/. In this case the process charged particle passing through the substance is described by a set of balance equations:

$$\frac{d\Phi_{in}}{dt} = -\Phi_{in}\sum\sigma_{in,kn'} + \sum\sigma_{kn',in}\Phi_{kn'} \qquad (3)$$

where Φ_{in} is the relative number of ions with charge i in n' excited state, $\sigma_{kn', in}$ is the cross section of ion transformation from the n' excited state with charge k into the n excited state with charge i. The number of states entering the equation system (3) was determined from the condition that the excited ion cannot capture the electron into the excited state with the dimensions exceeding an average distance of about $2.6.10^{-8}$cm between atoms in the carbon stripper and was changed from 9 for lithium ions, 20 for nitrogen ions and 35 for neon ions. The values of the cross sections of electron losses were obtained from the dependence of these cross sections on their binding energy and those of the electron capture cross sections were determined in the OBK approximation and normalized to the total cross section of electron capture.

The calculations of the equilibrium thicknesses have revealed that in the low ion energy region, $E \lesssim 0.1$ MeV/n the equilibrium thicknesses in the solid target are much higher than for gaseous media. In particular, for nitrogen ions at E = 0.1 MeV/n the equilibrium thickness of the carbon stripper is by an order of magnitude higher than that in the gaseous nitrogen target. With increase in the ion energy E due to increased likelihood of electron capture into the ion ground state this difference decreases and at $E \gtrsim 10$ MeV/n the T values for ions with $Z \leq 7$ do not practically depend on the aggregate state of the substance.

Fig.4 presents the minimum thicknesses T_z of the carbon stripper where the Li, B, N and Ne ion beam contains Φ_z = 0.9 ions having lost all their electrons. The values Φ_z =0.9 are reached in the thickness region $T_z > 1.6.10^{17} \times E^{1.6}$ atom/cm^2(the energy value E is expressed in MeV/n). In the increase of ion energy E the carbon stripper thickness also increases. In the high velocity limit when two charge components, φ_{z-1} of hydrogen-like ions and of nuclei only remain in the ion beam the value of T_z is found from:

$$T_z = \frac{\ln\left(\frac{1}{1-\varphi_z}\right)}{\sigma_{z-1,z} + \sigma_{z,z-1}} \tag{4}$$

Basing on these calculations it is supposed to use a carbon stripper 100 $\mu gr/cm^2$ in thickness, which should provide ion stripping up to oxygen at an efficiency of 99%. The charge exchange injection of heavier ions (including neon) in the IAE cooler is very doubtful.

References

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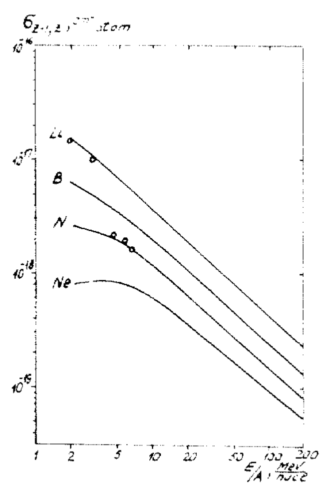

Fig.1. Dependence of the cross section of loss of the last electron on the energy in nitrogen for $^7Li^{2+}$, $^{11}B^{4+}$, $^{14}N^{6+}$, $^{20}Ne^{3+}$ ions. The circles denote the experimental values /3,4/.

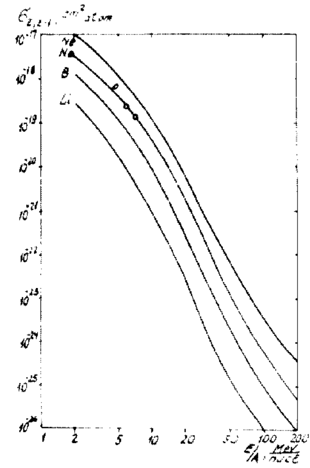

Fig.2. Dependence of the electron capture cross section on the energy in nitrogen for $^7Li^{3+}$, $^{11}B^{5+}$, $^{14}N^{7+}$, $^{20}Ne^{10}$ nuclei. The circles denote the experimental data /4/.

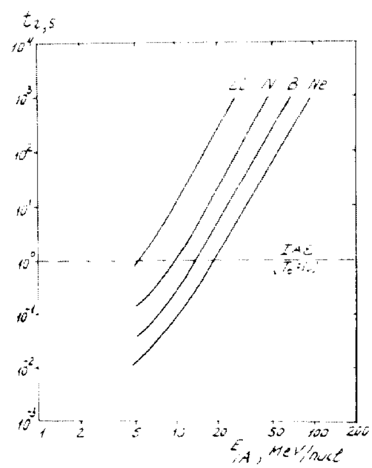

Fig.3. Dependence of the beam lifetime tr (intensities decreased by E times) on the energy of Li, B, N, and Ne nuclei circulating through a 10^4 atom/cm^2 thick target (nitrogen). For the IAE cooler the time allowed for experiment is Te=1sec.

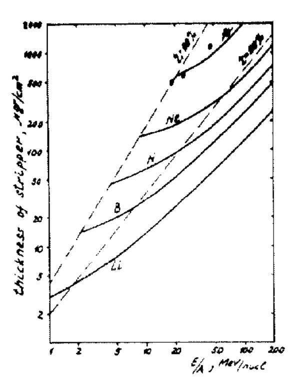

Fig.4. Dependence of the minimum stripper thickness for complete stropping of Li^{2+}, B^{4+}, N^{5+}, Ne^{9+} ions (the dashed line shows stripping up to η=90% and η=99%). The circles denote the experimental data.