УДК 539.189.2
539.12...18
539.12.125.46

METHOD OF THE IN-FLIGHT PRODUCTION OF EXOTIC SYSTEMS IN THE CHARGE-EXCHANGE REACTIONS

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Study of exotic few-body systems is of great interest in the investigation of the fundamental physical principles. The efficient method for production of exotic systems in the charge-exchange reactions is proposed. In this method, the reactions take place in-flight in the overlapping area of two particle beams. The beams of initial particles are supplied with a storage ring and either with another storage ring or a linear (electrostatic) accelerator. Advantages of this method are large cross sections of the charge exchange reactions, the absence of losses and interaction with medium. The production of positronium, protonium, antihydrogen and ions of the antiprotonic helium isoelectronic sequence is considered, possible yields are estimated and some problems of measurement on the beam of produced particles are discussed.

The investigation has been performed at the Bogoliubov Laboratory of Theoretical Physics and Laboratory of Nuclear Problems, JINR.

Метод образования экзотических систем на лету в реакциях перезарядки

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Изучение экзотических систем нескольких тел представляет значительный интерес для исследования фундаментальных физических принципов. Предлагается эффективный метод образования экзотических систем в реакциях перезарядки. Реакции происходят на лету в области перекрытия двух пучков частиц. Пучки реагирующих частиц образуются в накопительном кольце и либо в другом накопительном кольце, либо в линейном (электростатическом) ускорителе. Преимуществами данного метода являются большие сечения реакций перезарядки, отсутствие потерь и взаимодействия со средой. Рассмотрено образование позитрония, протония, антиводорода и ионов, принадлежащих к изоэлектронной последовательности антипротонного гелия. Оцениваются возможные скорости их образования и обсуждаются некоторые проблемы измерений на пучке образовавшихся частиц.

Работа выполнена в Лаборатории теоретической физики им. Н.Н.Боголюбова и Лаборатории ядерных проблем ОИЯИ.

I. Introduction

During the last years, studies of exotic few-body systems containing stable antiparticles, positron e^+ and antiproton p, attract much attention as a tool for the investigation of the fundamental physical principles. The production of these systems as a target and also experiments meet essential difficulties due to interaction with media. The efficient method providing the production of a beam of exotic systems is proposed in this paper.

This method has its roots in the electron cooling of the particle beam circulating in the storage ring [1]. The recombination of electrons and particles in the beam, being a parasitic effect for the electron cooling, was proposed for the production of new systems.

The essence of the method under consideration is the in-flight production of the above-mentioned systems in charge-exchange reactions. The cross sections of these reactions are of an order of the geometrical atomic cross section $\sigma_G = \pi a_0^2$ (a_0 is the Bohr radius) that is large enough to achieve a substantial yield of the produced particles. As will be discussed below, the cross section of some reactions significantly exceeds the geometrical value σ_G, and an additional enlargement of the cross section can be obtained by tuning the relative velocity of two particle beams.

Production of the positronium, protonium, antihydrogen and ions of the antiprotonic helium isoelectronic sequence is considered, the yield of these particles is estimated and possible measurements on the beam of produced particles are briefly discussed.

II. Method of Production

The storage ring is proposed as a source of the «exotic» particles such as positrons and antiprotons, whose beam intensities, as a rule, are limited due to the complicated generation method. Two different modes of operation are proposed to supply the other, «usual» ions necessary for the reactions under consideration. Of course, any exotic ions can be used as «usual» ions and the reaction of two exotic particles is possible. In the first mode (Fig. 1) the source of «usual» ions is another storage ring and in the second mode (Fig. 2) the «usual» ion beam is generated in a linear or an electrostatic accelerator. In both cases, the reactions take place in-flight in the common area of two beams. The angular and velocity spreads of a directed flux of the produced systems depend essentially on those of the initial particles. The secondary beam of a low enough momentum spread can be obtained by using the electron cooling of «exotic» particles in the storage ring [2].

The generation rate R is determined by

$$R = \sigma v_r l n_u N_e / C_e, \qquad (1)$$

where σ is the reaction cross section, v_r is the relative particle velocity, l is the length of the interaction region, where beams are overlapped, C_e is the circumference of the «exotic» particle storage ring, N_e is the «exotic» particle number in the circulating beam and the

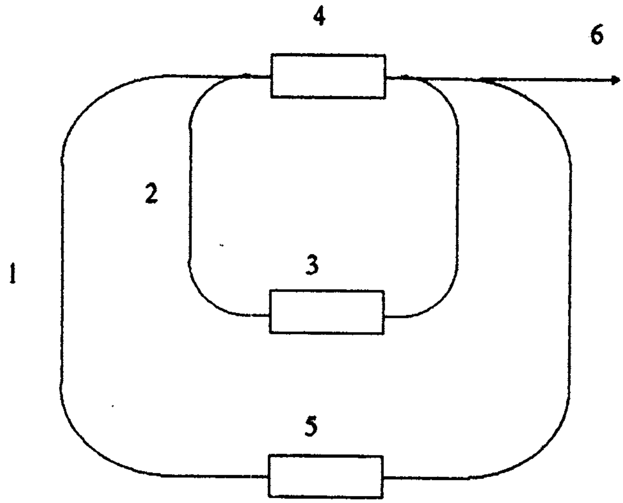

Fig.1. Method of production using two storage rings: 1 — «usual» particles storage ring, 2 — «exotic» particles storage ring, 3 — electron cooling of «exotic» particles, 4 — reaction area, 5 — electron cooling of «usual» particles, 6 — produced particles beam

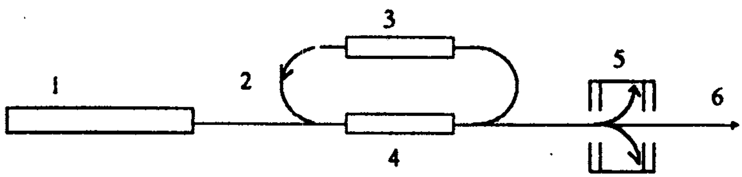

Fig.2. Method of production using a storage ring and an accelerator: 1 — accelerator of the «usual» particles, 2 — «exotic» particles storage ring, 3 — electron cooling of «exotic» particles, 4 — reaction area, 5 — «usual» particles collector (energy recuperation), 6 — produced particles beam

«usual» particle density in the interaction region n_u can be determined in two operation modes as

$$n_u = \begin{cases} \dfrac{N_u}{SC_u}, & \text{1st mode} \\ \dfrac{\dot{N}_u}{Sv_0}, & \text{2nd mode.} \end{cases} \tag{2}$$

Here N_u is the «usual» particle number in the storage ring of the circumference C_u, S is the largest of two beam cross sections, $\dot{N}_u$, v_0 are the ion flux and average particle velocity in the second mode. It is worthwhile to mention that the regime of bunched beams [2] brings a gain if the unbunched beam intensity is far from the space charge limit.

One of the essential advantages of this method is that the energy of colliding particles in the center of mass frame can be easily tuned by changing the cooling electron energy to achieve the largest yield and the desired quantum state of the produced systems.

In the second mode of operation, it is supposed to apply the so-called energy recuperation. In this scheme the main part of the ion beam, passed through the reaction area, decelerates in the electrostatic field and recovers a significant part of the accelerator power. In this way, the power consumption is reduced, the problem of the ion collection is solved and, as a result, the background conditions are significantly improved.

III. Positronium Production

The reaction

$$e^+ + \mathrm{H}^- \rightarrow \mathrm{Ps} + \mathrm{H} \tag{3}$$

is the most attractive for positronium production due to small binding energy $E_B \sim 0.76$ eV and large size $\sim 4a_0$ of the negative hydrogen ion H^-. The positronium can be formed at least in six states (1s, 2s, 2p, 3p, 3d) even at zero kinetic energy of the colliding e^+ and H^-. The cross section of the reaction (3) can be estimated as $10\sigma_G$ for the kinetic energy in the center of mass frame of an order of the characteristic atomic energy ~ 10 eV. Using this estimate and optimistic intensities of the circulating e^+ and H^- beams $N_{e^+} = 10^8$, $N_{\mathrm{H}^-} = 10^9$ for H^- beam energy 0.5 MeV, one can obtain the positronium generation rate on the level of $3 \cdot 10^7$ s^{-1} for $C_e = C_u = 15$ m, $l = 1.5$ m, $S = 3$ mm^2. This rate is significantly higher in comparison with the electron-positron radiative recombination method of the positronium in-flight production [2]. The available intensities of circulating particles are mainly limited by the beam space charge.

The advantage of the second mode of operation is the possibility of using the H^- beam of high intensity. Nowadays, the 0.5 MeV H^- beams of the DC of an order of few amperes are available [3]. Using the H^- ion current density of 1 A/cm^2 and the above mentioned parameters of the e^+ storage ring, one can obtain the positronium generation rate of $R = 10^{10}$ s^{-1}. Of course, the average flux of positronium will be limited by the positron storage rate in the ring. Despite of a comparatively large ion temperature $T \sim 1$ eV of the intensive H^- beam in the second mode of operation, the temperature of the produced positrinium is of the same order for both modes. The reason is that due to the mass difference of a positron and an H^- ion, the H^- ion velocity spread is much less than the positron one and the positronium temperature is determined mainly by the temperature of light particles, i.e., positrons.

It is reasonable to assume the significant production rates of the excited positronium due to both a larger size of these systems and decreasing the energy released in the reaction.

One should note that the lifetime or ortho-positronium in the ground state ~ 142 ns corresponds to a decay length ~ 1.4 m for the considered particle energy. For this reason, the particle energy should be increased if a larger length is necessary. Among excited states, the 2s state is metastable and its lifetime exceeds the ground state lifetime by a factor of eight. As a result, one should take into account the application of the 2s positronium in the described experiment.

VI. Antiprotonic Helium Isoelectronic Sequence

The metastable antiprotonic helium atom $He^{+}\bar{p}$ recently discovered [4.5] is a new few-body system consisting of a helium nucleus, an electron and an antiproton. These exotic atoms carry an extremely large total angular momentum $L \sim 30$—40 and survive for an enormous time (about tens of microseconds in comparison with the mean lifetime of antiprotons stopped in media $\sim 10^{-12}$ s). One can consider the antiprotonic helium as a representative of a new kind of exotic systems consisting of an arbitrary nucleus, an electron and an antiproton. Similarly to the two-electron ions, the set of these systems can be called the antiprotonic helium isoelectric sequence. Note that calculations of eigen-energies [7] testify to the existence of metastable $Li^{++}\bar{p}$, the next member of the sequence. The charge exchange reaction

$$A^{Z}ee + \bar{p} \rightarrow A^{Z}\bar{p}e + e, \tag{4}$$

where A^{Z} denotes the nucleus of the charge Z, provides the effective production of new members of this sequence for $Z \geq 3$. As for the $Z < 3$ cases, one should mention that the reaction (4) cannot be used for the in-flight production. The neutrality of the helium atom excludes the possibility of antiprotonic helium production ($Z = 2$), and the existence of the long-lived $H^{-}\bar{p}$ system ($Z = 1$) is not probable.

Since the determination of the reaction (4) cross section is a complicated problem, one can roughly estimate it using the results of the semiclassical calculation of antiproton capture in helium [8]. The calculated capture cross section into $He^{+}\bar{p}$ states is of an order of σ_G in a wide region of the initial kinetic energy 2–20 eV. Next, the experimental value of the trapped antiproton fraction [4] is about 6 times as small as that given in [8] and the radius of $Li^{++}\bar{p}$ is smaller than the $He^{+}\bar{p}$ one due to a greater nuclear charge. Taking into account these facts, the pessimistic value for the $Li^{++}\bar{p}$-production cross section is estimated about $0.03\sigma_G$ for the above-mentioned initial kinetic energies. Using, in eq.(1), the intensities of the Li^{+} and $\bar{p}$ beams $N_{Li^{+}} = 10^{8}$, $N_{\bar{p}} = 10^{9}$ for the particle energy 0.5 MeV/amu, $C_{Li^{+}} = 15$ m, $C_{\bar{p}} = 80$ m one comes, in the first mode of operation, to the $Li^{++}\bar{p}$ generation rate about 500 s^{-1}.

In the second mode of operation with the straight ion beam and the circulating $\bar{p}$-beam even for the moderate Li^{+} beam intensity of 0.1 A/cm^{2}, the $Li^{++}\bar{p}$ generation rate about $R \sim 10^{5}$ s^{-1} can be achieved.

All the problems of experimental and theoretical investigaitons [9], [10] of $He^+\bar{p}$ concern also other members of the antiprotonic helium isoelectronic sequence. The discovery and investigation of these systems will shed a new light on the antiprotonic helium and allow a thorough study of the antiproton characteristics. Remind that $A^Z\bar{p}e$ ions do not survive in medium and can be studied only in-flight.

One of the important problems is the isotopic dependence of the antiprotonic helium properties. Only two stable helium isotopes ^3He, ^4He are used in the modern experiment. In this respect, the investigation of Z dependence of new members of the antiprotonic helium isoelectronic sequence is of clear importance.

As it follows from the results [8], the production of antiprotonic helium atoms with a fixed angular momentum is due to the capture of an antiproton with a fixed energy. For this reason, one can produce $A^Z\bar{p}e$ in the desired quantum state tuning the relative velocity of colliding ions. Another interesting feature of the produced systems is the alignment of their angular momenta in the transverse direction. The discussion of this topic can be found in [11].

V. Protonium Production

After removing one electron via Auger decay, the $A^Z\bar{p}e$ system became a hydrogenlike ion $Z\bar{p}$ being in the high angular momentum state. Spectroscopic study of these ions is of great interest. In a similar way, the protonium $p\bar{p}$ in the high angular momentum state can be obtained in the reaction

$$\bar{p} + \mathrm{H}^- \rightarrow p\bar{p} + e + e. \qquad (5)$$

Annihilation of this system is prohibited for a large enough angular momenta. A test of the fundamental symmetry [12] by comparing p and $\bar{p}$ properties is the most interesting application of the protonium. For the above-mentioned $N_{\bar{p}}$, N_{H^-}, $C_{\bar{p}}$, S values and the reaction (5) cross section $10\sigma_G$ at the center of mass energy 10 eV the protonium generation rate is about $3\cdot 10^8\ s^{-1}$.

VI. Reactions of the Secondary Beam

The intense secondary beam can be used further to carry another reaction with significant yield. Two important examples of this sort will be described in this section.

A. Antihydrogen Production. The positronium produced in the reaction (3) can be used further to study other atomic reactions. During the last years there has been much interest in the antihydrogen production. Following the paper [13] one can consider the reaction

$$Ps + \bar{p} \rightarrow \bar{\mathrm{H}} + e. \qquad (6)$$

The storage ring serving antiprotons should be added to the positronium generator described above to realize the reaction (6). The cross sections of this reaction have been calculated recently [14], [15] for a number of initial positronium and final antihydrogen states. In spite of quite different methods, the results of two calculations are similar to each other and provide a reliable estimate of the antihydrogen production rates. The cross section of the reaction (6) for the positronium in the ground 1s state has a maximum value of about $15\sigma_G$ at the center of mass energy about 5-10 eV. The cross section of the antihydrogen formation in the $n = 2$ states dominates other channels. For the positronium in the 2s, 2p states, the cross sections have maximum values of about $300\sigma_G$ at the center of mass energy 0.25-0.5 eV. In this case, the antihydrogen formation takes place mainly in the $n = 2$ states. Using this cross section estimates and the above-mentioned positronium production rate 10^{10} s^{-1}, one comes to the antihydrogen production rate 900 s^{-1} in the former case of the positronium in 1s state and $1.7 \cdot 10^4$ s^{-1} in the latter one.

B. Antiprotonic Helium. One can point out the two-stage antiprotonic helium production as another example. In the first stage the hydrogenlike ion $He^{++}\bar{p}$ is produced in the reaction

$$He^+ + \bar{p} \to He^{++}\bar{p} + e \tag{7}$$

and in the second stage the antiprotonic helium is produced in the reaction

$$He^{++}\bar{p} + H^+ \to He^{++}\bar{p}e + H. \tag{8}$$

In a similar way, using the above-mentioned parameters, He^+ current density of 0.1 A/cm^2 and σ_G as a cross section of the reaction (7), one can obtain the $He^{++}\bar{p}$ production rate $R \sim 5 \cdot 10^6$ s^{-1}. Correspondingly, the rate of the antiprotonic helium production in the reaction (8) in the second mode operation for the cross section $\sim \sigma_G$ and H^- current density ~ 1 A/cm^2 will be about 20 s^{-1}.

VII. Studies of Exotic Systems In-Flight

The problem of the measurements on the beam of exotic systems arises in relation with the proposed method of the in-flight generation of these systems. The detailed discussion of this topic is not a goal of this letter and only the following remarks will be given. The ingenious method of resonant laser-induced spectroscopy [16] is applicable for the on-beam measurements with some modifications. Next, contrary to the in-medium production, the annihilation does not follow immediately after the Auger decay of $A^Z\bar{p}e$ and the Auger electrons can be detected beforehand. Some advantages arise from the high velocity movement of the system. Really, a significant Doppler shift can be used to reach the resonance conditions of the laser radiation in the particle rest frame. Also, the «Doppler-free» spectroscopy seems to be applicable. Another very promising method of in-flight measurements is the MW frequency spectroscopy and the so-called «atomic interferometer» scheme [17] allowing the high resolution study of the spectrum.

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Received on July 5, 1996.