Production of exotic hypernuclei and hyper-matter

A.S. Botvina

Institute for Nuclear Research, Russian Academy of Sciences, 117312 Moscow, Russia

Abstract

Pioneering experiments on production of hypernuclei can be performed with nuclotron beams on fixed targets, and at the future NICA facility. The peripheral collisions of relativistic ions are very promising for searching multi-strange and exotic hypernuclei which are not easy accessible with other experimental methods. In these experiments one can also get information on the Equation of State of hyper-matter around nuclear saturation density at low and moderate temperatures.

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In nuclear reactions at high energies strange particles (baryons and mesons) are produced abundantly, and they are strongly involved in the reaction process. The specifics of hypernuclear physics is that there is no direct experimental way to study hyperon–nucleon \((YN)\) and hyperon–hyperon \((YY)\) interactions \((Y = \Lambda, \Sigma, \Xi, \Omega)\). When hyperons are captured by nuclei, hypernuclei are produced, which can live long enough in comparison with nuclear reaction times. Therefore, a nucleus may serve as a laboratory offering a unique opportunity to study basic properties of hyperons and their interactions. Double- and multi-strange nuclei are especially interesting, because they are more suitable for extracting information about the hyperon–hyperon interaction and strange matter properties.

The investigation of hypernuclei allows to answer many fundamental questions: Studying the structure of hypernuclei helps to understand the structure of conventional nuclei too \([1]\) and it leads to an extension of the nuclear chart into the strangeness sector \([2]\). Hypernuclei provide a bridge between traditional nuclear physics (dealing with protons and neutrons) and hadron physics. Strangeness is an important degree of freedom for the construction of QCD motivated models of strong interactions \([3]\). Hyperons are also very important in many astrophysical sites, e.g., they are abundantly produced in nuclear matter at high densities, which are realized in the core of neutron stars \([4]\). The only way to describe realistically these physical conditions is to study the hyperon interactions in laboratory, and select theoretical models which pass the careful comparison with experimental data.

It has been realized that the absorption of hyperons in spectator regions of peripheral relativistic ion collisions is a promising way for producing hypernuclei \([5–8]\). The basic mechanisms of such reactions were well established in analysis of collisions of conventional nuclei: Nucleons in the overlapping zone between the projectile and the target (participants) interact intensively with each other and produce many new particles including strange ones. These particles can re-scatter and propagate further towards the non-overlapping parts of nuclei (spectator residues) and can be captured there, if their relative kinetic energy is smaller than their potential in nuclear matter. This mechanism will lead to formation of excited normal spectators and hyper-spectators, which later on disintegrate into ordinary and hyper-fragments \([9]\). Very peripheral collisions lead to spallation of the normal nuclei and to fission of heavy ones. In mid-peripheral collisions, when temperatures of excited spectators reach several MeV, multifragmentation reaction takes place, and this allows for investigation of the Equation of State (EOS) in the region of the nuclear liquid-gas phase.
transition \[10,11\]. Since the $\Lambda$ potential in nuclear matter is of the same order as the nucleon one we expect that similar processes will occur with hyper-spectators too. Such reactions may give access to heavy and exotic hypernuclei, as well as to very strange nuclei beyond $S=–2$ \[8\]. It was also predicted that the relative yields of hypernuclei produced in these reactions can reveal important information about their properties and provide a unique way for experimental studying hyper-matter at relatively low temperatures ($T\lesssim 10$ MeV) \[9\]. These are important advantages of the proposed measurements over experimental methods used presently in hyper-physics, which are mostly limited by investigations of hypernuclei with $S=–1$ in ground and weakly-excited states.

Actually, early experiments with light-ion beams at the LBL \[12\] and JINR \[13\] have demonstrated that hypernuclei can be formed in such reactions. Recently the HypHI collaboration at GSI Darmstadt has reported first results on the production of light hypernuclei in the disintegration of 2 GeV per nucleon $^6$Li projectiles impinging on a $^{12}$C target \[14\]. This experiment has confirmed the feasibility to produce hypernuclei abundantly in peripheral ion collisions. The observed production of $^3\Lambda$H is by about a factor of three larger than the production of $^4\Lambda$H. In a still preliminary analysis also indications for a significant bump in the $\pi^–$-deuteron invariant mass distribution were found \[15\]. If confirmed in the ongoing analysis this observation could be interpreted as the formation of slightly bound $\Lambda$-neutron systems ($\Lambda n$ and $\Lambda nn$), which seem to dominate over other hypernuclei.

It was theoretically demonstrated that this reaction can be explained within a hybrid approach including dynamical stage of production and capture of hyperons by spectators and statistical stage describing decay of such excited spectators into hypernuclei \[16,17\]. The first stage of this collision process was described within the transport Dubna cascade model (DCM) \[18,19\] taking into account absorption of $\Lambda$-hyperons \[8\]. The generalized for hypernuclei Fermi-break-up model \[20\] was used for the second stage. The DCM calculations of $^6$Li (2 A GeV) + $^{12}$C collisions predict formation of a broad ensemble of projectile residues with captured $\Lambda$ hyperons. After integration over all impact parameters this ensemble is shown in Fig. \[11\]. The following evolution depends on excitation energy of these residues: Their baryon content will not change practically if the excitations are low. In the case of high excitations the residues will lose nucleons and small final hypernuclei will be produced predominantly, including exotic $\Lambda n$ hyper-systems \[17\].

We emphasize specially that the exotic $\Lambda$–neutron systems were never observed previously.
with traditional methods of hyper-physics, which use mainly a capture of hyperons produced by hadrons and leptons of high energy in nuclei without their excitation. The reason may be that a very low binding energy expected for the Λn systems (around few tens keV) can not be seen in such direct interactions releasing particles with large energy. On the other hand, the decay of moderately excited hyper-systems into small hypernuclei [20] is rather sensitive to the tiny binding energy. Therefore, the new reaction mechanism realized in peripheral collisions of relativistic ions makes possible to produce and investigate exotic hypernuclear species.

Another new important possibility is to study fragmentation and multifragmentation of hyper-matter produced in peripheral collisions of heavy ions. In this case one can address the EOS of hyper-matter at moderate temperatures as previously it was done for conventional matter [21]: The method is to analyze the yields of fragments and hyper-fragments and their velocity correlations, which contain information about hyperon interaction in medium. For illustration, Fig. 2 shows probabilities for producing spectator residues with different numbers of captured Λs, in collisions of proton on gold and gold on gold at energies 2 and 20 GeV per nucleons [8]. The dynamical stage of these reactions was described by DCM [18, 19] and UrQMD (Ultra-relativistic Quantum Molecular Dynamics) [22, 23] models. One
FIG. 2: Probability for formation of conventional and strange spectator residuals (top panels), and their mean mass numbers (bottom panels) vs the number of captured Λ hyperons (H), calculated with DCM and UrQMD model for p + Au and Au + Au collisions with energy of 2 GeV per nucleon (left panels), and 20 GeV per nucleon (right panels) [8]. The reactions and energies are noted in the figure by different histograms.

can see that both in proton-nucleus and nucleus-nucleus collisions the hyper-spectators can be formed abundantly. For example, the fraction of excited spectator residues with one Λ is in the range of from 0.1% (for the case of 2 GeV proton) to few percent of the total yield at 20 GeV. At the nuclotron’s beam energy of 4.5 A GeV the estimated probability of one Λ capture will be around 0.3% for p + Au and more than 1% for Au + Au collisions. The probabilities for capturing two Λs will be by nearly two order lower, and the probability for three Λ to be captured is around $10^{-6}$. However, these reaction probabilities are quite
sufficient for hyper-physical experiments which are usually adjusted for cross-sections about few nanobarns. The absorption of a higher number of hyperons is also feasible. This new mechanism opens a unique opportunity to produce and study multi-strange systems, which are not conceivable in other nuclear reactions. As discussed, later on the hot spectators disintegrate, and final fragments with products of weak decay of hypernuclei can be measured by detectors. Statistical models, see refs. [9, 10, 20], can be used to describe this stage of the process. Relativistic spectators have also obvious experimental advantages: Because of the Lorentz factor their lifetime is longer, the projectile hyper-fragments can travel a longer distance. This makes possible to use sophisticated vertex detectors and fragment separation technique for their identification.

One should remember, that the considered reaction process is qualitatively different from the production mechanisms of light hypernuclei coming from decay of very excited ($T \sim 160$ MeV) fireballs with strangeness admixture, which are formed in central relativistic heavy-ion collisions, . In this case coalescence-like processes are most probable for cluster production. There is hard to expect production of big and weakly bound nuclei, because of a large energy deposited in the fireball [24, 25]. Nevertheless, after full construction of the NICA facility, this kind of measurements may also be done by colliding relativistic beams and detecting species coming from the midrapidity region.

In conclusion, an advantage of the proposed novel experiments is that they can be already performed at the first stage of the NICA project with nuclotron beams by using the fixed targets. It is instructive that the very first experimental identification of a hypernucleus was performed in similar collisions: This event was observed in a multifragmentation reaction induced by a cosmic energetic proton or ion in photo-emulsion [26]. Recently, encouraging results in studying spectator hypernuclei were obtained in GSI experiments [14, 15]. As we have shown theoretically [8, 9, 16, 17, 20], the process of formation of moderately-excited hyper-nuclear systems ($T \approx 1 - 10$ MeV) in peripheral collisions of relativistic ions with their subsequent disintegration is a natural way to produce new and exotic hypernuclei. We know also from studies of conventional nuclei [10, 21] that investigation of such systems can provide effective methods to extract the EOS of hyper-matter at densities around the nuclear saturation density. Hypernuclear physics will benefit strongly from exploring the new production mechanism realized in peripheral ion collisions and the novel detection technique.
associated with fragmentation reactions of excited nuclei.

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