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STRUCTURE EFFECTS ON REACTION MECHANISMS IN COLLISIONS INDUCED BY HALO AND WEAKLY BOUND NUCLEI AROUND THE COULOMB BARRIER

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The study of reaction mechanisms in collisions induced by halo and/or weakly bound nuclei around the Coulomb barrier has recently been the subject of many theoretical and experimental papers. Here we discuss our present understanding of some aspects of such a topic by briefly summarizing experimental data obtained by different authors with particular attention to some results obtained in the last years by our collaboration.

1. Introduction

With the increasing number of radioactive beam facilities available today, it is now possible to study nuclear reactions induced by neutron or proton rich nuclei. Some of such nuclei have extremely low break-up thresholds (of the order on 1 MeV or even less) and, in some cases, the last weakly bound nucleon(s) may form a large diffuse halo or a skin around a well bound core [e.g.1]. In the last years a lot of work has been performed aiming to understand which effects one should expect on reaction mechanisms around the Coulomb barrier when using halo nuclei as projectiles or, more in general, weakly bound nuclei not having the peculiar halo structure. A recent review on this topic can be found in [2]. In the following we discuss our present understanding of some aspects of such a subject, mainly focusing on fusion reactions, by briefly summarizing experimental data obtained by different authors with particular attention to some results obtained in the last years by our collaboration.

The theoretical description of the reaction dynamics in collisions induced by halo nuclei (or more in general weakly bound nuclei) is quite difficult. Within a simple semiclassical scheme, one might expect that direct processes like break-up or transfer are favoured by the low binding energies and the long extended tail of halo nuclei. The role of break-up on fusion is difficult to model. In fact, on one side, one can think at break-up as a process which prevents the capture of the incoming projectile suppressing fusion. However, on the other side, it is well known that in Coupled Channels (CC) calculations the presence of a strong open reaction channel can be responsible for an enhancement of the fusion cross-sections around and below the barrier. Some of the recent models are based on Continuum Discretized Coupled Channels (CDCC) calculations; however, not all the models reach similar conclusions. As an example K. Hagino et al. [3] computed the fusion excitation function around the barrier for $^{11}Be + ^{208}Pb$ within the CDCC frame finding an enhancement of complete fusion below the barrier and a suppression above. A. Diaz-Torres et al. [4] performed a more sophisticated CDCC calculation for the same system including the effects of continuum-continuum couplings. They found enhancement of complete fusion only deeply below the barrier and suppression in the rest of the energy range. M. Ito et al. [5] developed a model which follows the time evolution of a three body system (halo nucleon, core, and target) and concluded that, in a collision induced by a neutron halo nucleus, one should expect a suppression of the fusion cross-section in all the energy range.

The experimental study of reaction dynamics around the Coulomb barrier, in collisions induced by radioactive weakly bound nuclei, is quite difficult mainly due to the low currents ($10^5 \div 10^6$ pps) of radioactive beams coupled with the low cross-sections of some reaction channels especially below the barrier. In the following we will briefly summarize experimental data obtained by different authors with particular attention to some results obtained in the last years by our collaboration.

2. Some experimental results in collisions induced by halo nuclei

The first system were different reaction channels were studied was the collision $^6He + ^{209}Bi$. Different experiments have been performed on this system [e.g. 6 - 8]. The results show an enhancement of the fusion cross-section around and below the barrier for the $^6He + ^{209}Bi$ system when compared to the predictions of calculations [6] and with the fusion excitation function for $^4He + ^{209}Bi$ [9]. The authors evidenced the presence of a strong yield of alpha particles saturating most of the total reaction cross-section [e.g. 7] which have been attributed mainly to transfer reactions events but also to break-up reactions [8].

We have recently extended the measurement of the fusion excitation function for $^6He + ^{64}Zn$, we had already measured at energies around the Coulomb barrier [10], to energies up to 1.7 the Coulomb barrier. As comparison, the reaction ^{4}He + ^{64}Zn was also measured. The experiment has been performed at the radioactive beam facility of Louvain la Neuve. We have measured the fusion excitation function in the energy range 12 MeV ≤ E_{cm} ≤ 16 MeV using the same technique described in detail in [10] and summarised in the following. The fusion cross-section has been measured by using an activation technique detecting the atomic X-rays emitted from the radioactive evaporation residues (E.R.) after decaying by Electron Capture (E.C). The experimental set-up is sketched in Fig. 1. An array of Si strip detectors surrounding a thin (~500 μg/cm^2) ^{64}Zn target was used to detect the light particles (^{6}He, α and p) produced in the reaction. The thin ^{64}Zn target was angled at 45° in order to allow detection of particles emitted at 90°. The angular range covered was 5° ≤ θ ≤ 120°. He isotopes were discriminated from H using the time of flight (TOF) information.

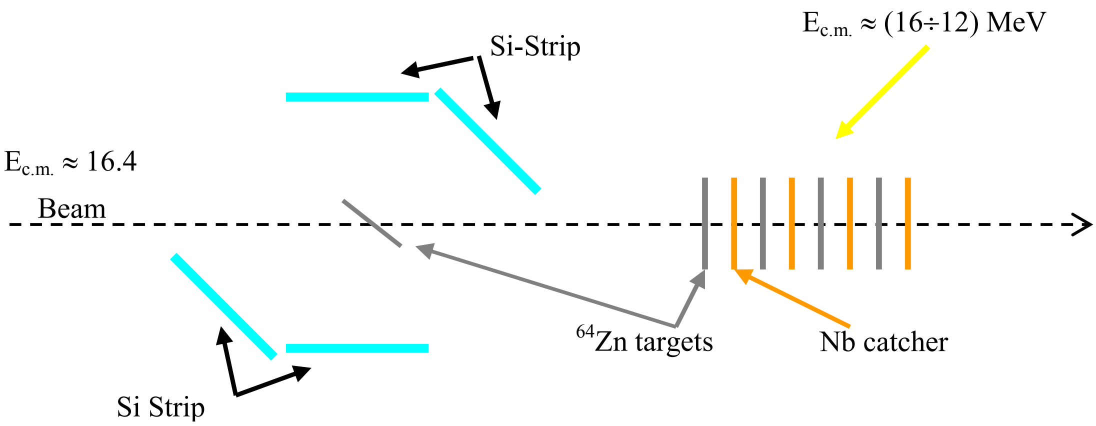

Fig. 1. Sketch of the experimental setup.

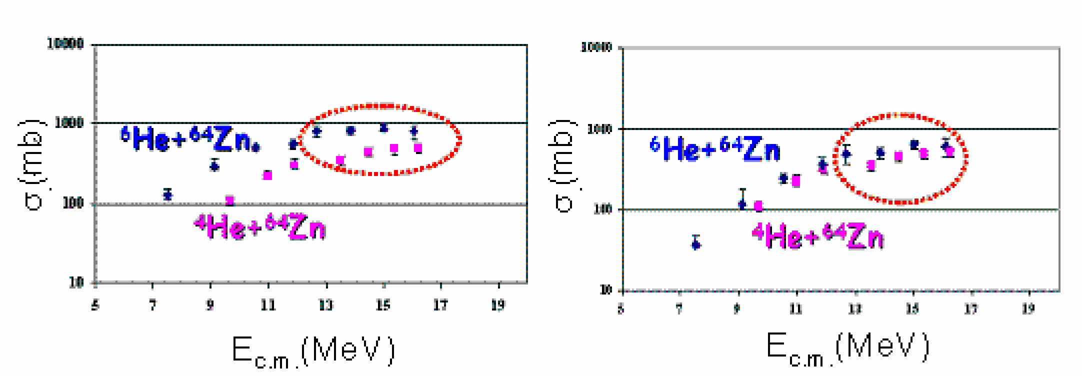

Fig. 2. Left panel: excitation functions for the production of heavy residues in the collisions ^{6}He + ^{64}Zn and ^{4}He + ^{64}Zn. The points inside the ellipse are new experimental results; the other points are the results of [10]. Right panel: same as left panel but the cross-section for ^{65}Zn measured for ^{6}He + ^{64}Zn has been substituted by the one predicted by statistical model calculations. (See text for details).

Downstream the thin ^{64}Zn target a stack of thick ^{64}Zn targets (~2 mg/cm^2), each followed by a Nb catcher (~3.5 mg/cm^2), was irradiated by the same beam. Short and long activation runs were performed to optimize the production of E.R. with different half-lives. The catcher thickness was chosen in order to stop the E.R. produced in the previous ^{64}Zn target and to degrade the beam energy. The activity of the irradiated targets was measured off-line using Pb shielded large area Si(Li) detectors whose intrinsic efficiency is 100 % for X-ray energies of our interest (6 - 11 keV). The advantage of measuring X-rays is the very low background that can be obtained with proper passive shields which allowed us to measure with X-ray counting rates as low as 0.5 counts/h. Although different isotopes of the same element are not separated in the X-ray spectra, they have been identified by their half lives following the activity curves as function of time in the way explained in [10]. The excitation functions obtained by summing up the contribution of all radioactive heavy fragments produced in the two reactions ^{4,6}He + ^{64}Zn, extracted with the above described technique, are shown in Fig. 2 (left panel). An apparent enhancement of the fusion cross-section seems to be present in the reaction induced by the ^{6}He beam. However as observed in [10], this enhancement could be due to the contribution of 1n and 2n transfer which produces the radioactive ^{65}Zn nucleus, also produced in the 1α+1n evaporation channel following fusion reactions. If one subtracts the contribution due to transfer using the same procedure used in [10], i.e. replacing the measured value for ^{65}Zn with the one calculated using the statistical model code CASCADE, one obtains the results shown in Fig. 2 (right panel). From this comparison it seems that no effect on the fusion cross-section due to the halo structure of the ^{6}He nucleus is present in the energy range explored. On the contrary we observed, at all the energies studied, a suppression of elastic scattering in the collision induced by ^{6}He corresponding to an enhancement of the total reaction cross-section (e.g. Fig. 3).

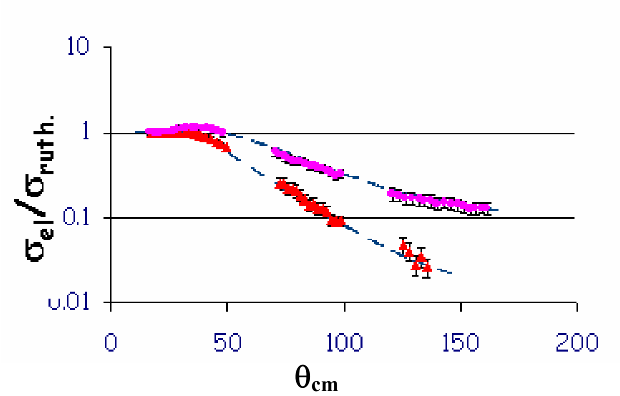

Fig. 3. Elastic scattering angular distributions, normalized to Rutherford scattering, for ^{6}He + ^{64}Zn (closed triangles) and ^{4}He + ^{64}Zn (closed dots) at E_{cm} = 12.4 MeV. The total reaction cross-sections extracted by the optical model fits (dashed lines) are 1450 ± 130 mb and 650 ± 80 mb for the ^{6}He and ^{4}He induced reactions respectively.

This enhancement has been attributed, as discussed in [10], to direct reaction mechanisms like transfer and break-up.

A study of the collisions ^{4,6}He + ^{65}Cu, (with a target of similar mass as our ^{6}He+^{64}Zn) was recently performed by A. Navin et al. [11]. In this experiment only two energy points, at above barrier energies, have been studied for ^{6}He. The results, obtained by looking at gamma-particle coincidences, are in agreement with our conclusions for ^{6}He + ^{64}Zn. In fact a good agreement between statistical model calculations and the experimental relative yield of heavy residues has been found with the exception of ^{66}Cu. The analysis of gamma-particle coincidences has shown that the observed extra yield for ^{66}Cu is actually due to transfer reactions and no effects on fusion due to the structure of ^{6}He have been evidenced.

Another reaction studied by some of us within a collaboration of different European groups was the collision ^{6}He + ^{238}U [12]. This experiment was performed at the radioactive beam facility of Louvain la Neuve. Fission excitation functions for ^{6}He + ^{238}U and ^{4}He + ^{238}U were obtained by looking at fission fragments emitted in coincidence with a relative angle close to 180°. The fission excitation function for ^{6}He + ^{238}U is strongly enhanced around and below the barrier when compared with the one for ^{4}He + ^{238}U. The analysis of the light charged particles emitted in coincidence with the fission fragments showed that the enhancement in the fission excitation function for ^{6}He + ^{238}U is not due to fusion but to direct processes (mainly two neutron transfer). The fusion-fission excitation functions for ^{6}He and ^{4}He on ^{238}U are rather similar and no evident effects on the fusion process due to the structure of ^{6}He have been evidenced [12].

Although most of the available experimental results have been obtained with ^{6}He beams, fusion excitation functions for the collisions ^{9,10,11}Be + ^{209}Bi have also been measured by C. Signorini et al. [13] at energies close and above the barrier. The three Be isotopes have very different structure: weakly bound cluster structure for ^{9}Be, well bound for ^{10}Be and weakly bound halo structure for ^{11}Be. However, within the error bars, the three measured fusion excitation functions are similar and no effects due to the different structure of the three Be isotopes were evidenced.

In summary, for those experiments where this was studied [7, 10 - 12], a large yield for direct reactions due to transfer and break-up events has been evidenced by different authors in collisions induced by weakly bound halo nuclei. Measuring fusion cross-sections with low intensity radioactive beams is not an easy task, and most of the available data are not really exploring the region below the barrier. Not all the experimental results concerning the fusion excitation functions seem to indicate the same behaviour. In fact, the enhancement of fusion around and below the barrier evidenced in ^{6}He + ^{209}Bi is not seen (within the error bars and energy range explored) in the other systems studied although, as said, few data exist below the barrier.

3. Some experimental results in collisions induced by weakly bound nuclei

Reactions induced by weakly bound nuclei which do not have the peculiar halo structure on targets having different masses have also been studied in the last years. Most of the experiments have been performed by using as projectiles the least bound stable nuclei in nature (^{6,7}Li ^{9}Be). This allows using intense beams and collecting good quality data; however data concerning reactions induced by weakly bound radioactive beams also exist.

A systematic study of fusion reactions induced by ^{6,7}Li and ^{9}Be on heavy targets (^{208}Pb, ^{209}Bi) has been performed by M. Dasgupta et al. [14]. The authors compared experimental complete fusion excitation functions with the results of CC calculations not including the effects of break-up. They concluded that in the region above the barrier there is a suppression of complete fusion of the order of 30 % due to the presence of incomplete fusion following break-up. No strong effects have been evidenced in the region below the barrier. The presence of complete fusion suppression was also confirmed by comparing experimental fusion excitation functions leading to the same compound nucleus via two different entrance channels. Results similar to the ones reported by M. Dasgupta et al. [14], indicating a complete fusion suppression above barrier, have also been reported by other authors for different colliding systems like, for instance, ^{6}Li + + ^{208}Pb [15] and ^{9}Be + ^{209}Bi [16]. Recently, we also studied the fusion-fission excitation function for ^{7}Be + ^{238}U using the same technique as for ^{6}He + ^{238}U [12] and within the same collaboration. Also in this case a suppression of complete fusion above barrier has been observed [17].

A systematic study of fusion reactions induced by ^{6,7}Li and ^{9}Be on the medium mass target ^{64}Zn is discussed in [18]. The separation of complete and incomplete fusion contributions, in collisions induced by light weakly bound nuclei on medium mass or light targets, is difficult since the same evaporation residues can be populated in complete and incomplete fusion reactions. The results of [18] suggest that the possible incomplete fusion contribution is small and, contrary to what observed for heavy targets, no fusion suppression is evidenced due to the structure of the projectiles. Similar results were no fusion suppression above barrier was evidenced, were published also by other authors [e.g. 19].

The study of fusion reactions between light weakly bound nuclei above the barrier leaded to apparently contradictory results. As an example, according to some authors [e.g. 20 and refs. therein], fusion excitation functions in colliding systems involving the least bound stable nuclei in nature (^{6}Li, ^{7}Li, ^{9}Be) show suppressed values of the fusion cross-section above the barrier which are, in some cases, up to 50 % lower than the expected calculated ones. The obtained results have been interpreted by assuming that the competition between fusion and break-up is reducing the fusion cross-section. On the other hand, other authors do not find hints indicating the presence of these suppression effects on the fusion cross-section [e.g. 21, 22 and references therein]. To further investigate collisions between light weakly bound nuclei, we decided to compare fusion cross-sections above the barrier for the systems ^{12}C + ^{10}B and ^{13}N + ^{9}Be leading to the formation of the compound nucleus ^{22}Na. The two colliding systems, leading to the same compound nucleus, are very similar. Therefore, in absence of structure effects, one would expect similar fusion excitation functions. However, in the collision ^{13}N + ^{9}Be one has a weakly bound radioactive projectile (S_p(^{13}N) = 1.9 MeV) impinging on a weakly bound target (S_n(^{9}Be) = 1.6 MeV). Therefore, our aim was to look for possible suppression effects of the fusion cross-section above the barrier in this collision between two light weakly bound nuclei. The reaction ^{12}C + ^{10}B has been studied using the stable beams accelerated by the tandem of the Laboratori Nazionali del Sud. The ^{13}N + ^{9}Be reaction has been studied at the radioactive beam facility of Louvain la Neuve using ^{13}N beams at 45 MeV having currents between 10^7 and 10^8 pps. For this last experiment, we used thin (200 μg/cm^2), self supporting targets of ^{9}Be which have been developed by the target laboratory of the Laboratori Nazionali del Sud. Charged particles emitted in the studied collisions have been detected, and charge identified using an array of monolithic silicon strip telescopes [23], in the angular range ~(3 ÷ 45°). Such telescopes [23] have the ΔE and residual energy stages integrated in the same silicon chip obtaining ΔE stages of the order of 2 μm including the dead layers. In both collisions the fusion cross-section has been extracted by integrating the evaporation residue angular distributions. To obtain the absolute normalization factors for the cross-section, we normalized the elastic cross-section to the Rutherford one at small scattering angles. According to our results, the extracted fusion cross-section for ^{13}N + ^{9}Be at E(^{13}N) = 45 MeV is similar to the ones for ^{12}C + ^{10}B at similar centre of mass energies and there are no evident suppression effects of the fusion cross-section for the weakly bound light system ^{13}N + ^{9}Be. The experimental relative yields of the different evaporation residue for the two reactions are compared with the predictions of the statistical model Cascade in Fig. 4. Such a comparison is made at a fixed excitation energy of the compound nucleus E*(^{22}Na) ≈ 40 MeV which corresponds to E_{lab}(^{13}N) = 45 MeV for the ^{13}N + ^{9}Be reaction and E_{lab}(^{10}B) = 42 MeV for the ^{12}C + ^{10}B system. As one can see, the experimental relative yields for the two reactions are very similar and in good agreement with the predictions of statistical model calculations. This excludes the possibility to have a strong incomplete fusion contribution in the ^{13}N induced reaction due to the presence of the weakly bound proton. In summary, our preliminary results do not show strong suppression effects of the fusion cross-section for the weakly bound system ^{13}N + ^{9}Be. Moreover the comparison with the statistical model

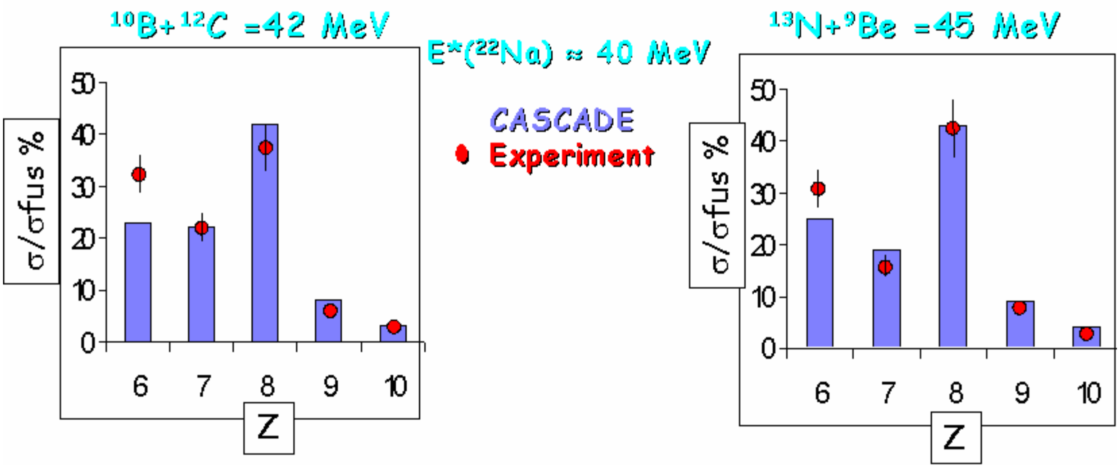

Fig. 4. Left panel: experimental (points) and calculated (histogram) relative yields of the different evaporation residues in the collision $^{10}B + ^{12}C$ at an excitation energy of the compound nucleus E*(^{22}Na) ≈ 40 MeV. Right panel: same as left panel but for the reaction $^{13}N + ^{9}Be$.

calculations appears to confirm that the reaction proceeds via complete fusion followed by particle evaporation.

4. Summary and conclusions

As discussed in section 2, different experimental results concerning the study of reaction mechanisms around the barrier in collisions induced by weakly bound halo nuclei have already been published [e.g. 6 - 13]. Different authors evidenced a large yield for direct reactions due to transfer and break-up events in collisions induced by such nuclei [8, 10 - 12]. Measuring fusion cross-sections with low intensity radioactive beams is not an easy task and most of the available data are not really exploring the region below the barrier. Not all the experimental results concerning the fusion excitation functions seem to indicate the same behaviour. In order to further clarify this topic new data in collisions induced by different nuclei and extending below the barrier are necessary.

Collisions induced by weakly bound nuclei not having the peculiar halo structure on targets of different masses have also been studied [e.g. 14 - 22]. Different authors agree that on heavy targets one has a suppression of complete fusion above barrier due to the structure of the incoming projectiles [14 - 17]. With medium mass targets it is difficult to separate the contribution of complete and incomplete fusion. The existing data suggest that possible incomplete fusion contributions are small and, contrary to the heavy target case, no suppression effects on fusion have been evidenced [e.g. 18 - 19]. Different conclusions have been reached by different authors concerning the existence or not of fusion suppression in collisions between light weakly bound nuclei. Some results [e.g. 20 and refs. therein] suggest the presence of a strong fusion suppression in collisions above barrier between light weakly bound nuclei which, however, is not observed by other authors [e.g. 21 - 22]. Our data on $^{13}N+^{9}Be$ do not show any evidence for the presence of such suppression.

From the discussion so far, we believe that although many experimental and theoretical efforts have been performed in the last years, new data with different beams (possibly taken in exclusive experiments and/or experiments looking at once at elastic + all open reaction channels) and more theoretical efforts are needed for a complete understanding of the reaction dynamics in collisions between weakly bound nuclei around the Coulomb barrier.

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СТРУКТУРНІ ЕФЕКТИ В МЕХАНІЗМАХ РЕАКЦІЙ ЗІ СЛАБКОЗВ'ЯЗАНИМИ ТА ГАЛО-ЯДРАМИ У ВХІДНОМУ КАНАЛІ В ОБЛАСТІ ЕНЕРГІЙ КУЛОНІВСЬКОГО БАР'ЄРА

П. Фігуера, М. Скудері

Дослідження механізмів ядерних реакцій в процесах, що спричинені слабкозв'язаними та/або гало-ядрами при енергіях кулонівського бар'єра, на сьогодні стали темою багатьох теоретичних і експериментальних робіт. У даній роботі ми обговорюємо наше сучасне розуміння деяких аспектів цієї теми, узагальнюючи експериментальні дані різних авторів та звертаючи особливу увагу на деякі результати, отримані нашою колаборацією за останні роки.

СТРУКТУРНЫЕ ЭФФЕКТЫ В МЕХАНИЗМАХ РЕАКЦИЙ СО СЛАБОСВЯЗАННЫМИ И ГАЛО-ЯДРАМИ ВО ВХОДНОМ КАНАЛЕ В ОБЛАСТИ ЭНЕРГИЙ КУЛОНОВСКОГО БАРЬЕРА

П. Фигуэра, В. Скудери

Исследования механизмов ядерных реакций у процессах, вызванных слабосвязанными и/или гало-ядрами при энергиях вблизи кулоновского барьера, на сегодня являются темой многих теоретических и экспериментальных работ. В данной работе мы обсуждаем наше сегодняшнее понимание некоторых аспектов этой темы, кратко суммируя результаты, полученные разными авторами, и обращая особое внимание на результаты, полученные в последние годы нашей коллаборацией.

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