Letter of Intents to the ISOLDE and NTOF committee

Reaction mechanisms in collisions induced by a low energy ^{8}B beam.

A. Di Pietro[1], P.Figuera[1], A. Bonaccorso[2], M.Fisichella[1,3], J. Gomez-Camacho[4], M.Lattuada[1,5], M.Milin[6], A.Musumarra[1,5], M.G.Pellegriti[1,5], D. Santonocito[1], V.Scuderi[1,5,] D.Torresi[1,5], A.C. Shotter[7], E.Strano[1,5], N.Soic[8], M.Zadro[8].

1)INFN-Laboratori Nazionali del Sud, Catania, Italy
2)INFN-Sezione di Pisa, Pisa, Italy
3) Universita' di Messina, Messina, Italy
4) Departamento de Fisica Atomica Molecular Nuclear Universidad de Sevilla, and Centro Nacional de Aceleradores, Sevilla, Spain
5) Universita' di Catania, Catania, Italy
6)Department of Physics Faculty of Science University of Zagreb, Zagreb, Croatia
7) TRIUMF and University of Edinburgh, Edinburg, UK.
8)Division of Experimental Physics Ruder Boskovic Institute, Zagreb, Croatia

Spokespersons: A.DiPietro, P.Figuera

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Abstract

Huge efforts have been done in the last years in major laboratories around the world to understand the reaction dynamics around the Coulomb barrier with neutron halo nuclei. On the other hand the collision dynamics at the barrier with proton-halo nuclei is expected to be different, but almost no experimental data exist. To our knowledge, different international collaborations are proposing to investigate the above topic developing in-flight-separated ^{8}B beams. We believe that with the availability of a low intensity post accelerated ^{8}B beam, REX ISOLDE would be a unique facility allowing to collect, high quality data for the study of such an important topic.

1. Physics case

Evidences of ^{8}B p-halo structure

^{8}B is a drip line nucleus, with its very low threshold of 0.138 MeV against $^{8}B\rightarrow^{7}Be+p$ break-up is a good candidate for having a proton-halo structure. The existence of a p-halo in ^{8}B has been debated in the literature. The interaction cross-section measured at energies larger than 100 A MeV does not show enhancement with respect to the systematic of stable nuclei see e.g. [1,2] and therefore a regular size of ^{8}B was deduced. A reanalysis performed by Al-Khalili and Tostevin [5], of the high energy data [1], suggested that the previously assigned rms radius should be reassigned indicating a large extension of the last proton distribution beyond the core. At lower energies large enhancements of the interaction cross-section have been observed (see [3,4]).

A narrow momentum distribution of ^{7}Be is observed in ^{8}B break-up experiments performed at various

energies and on several targets; the momentum distribution is however influenced by the reaction mechanism so it does not necessarily reflect the characteristics of the valence proton wave function [6].
A long tail of the density distribution is deduced from the σ_R analysis in [3] indicating the existence of the halo whereas in [7] a weakly developed p-halo is claimed.
A large $\sigma_{1p}(^8B\rightarrow^7Be)$ removal cross-section is found in [8,9] which accounts for the difference between the interaction cross-sections $\sigma(^8B)$ - $\sigma(^7Be)$ [3]. This behavior indicates a p+^{7}Be configuration in the wave function of ^{8}B with a proton decoupled from the other nucleons thus supporting the p-halo existence in ^{8}B.
In summary, most of the existing results are in favor of a p-halo configuration of ^{8}B. Due to the presence of the Coulomb barrier which inhibits the occurrence of a halo in p-rich nuclei, ^{8}B is probably the only nucleus having a p-halo configuration in its ground state.

1.2 n-halo induced reactions

Reactions induced by n-halo nuclei have been extensively studied, in a wide range of energies and on different targets, in order to understand the role played by the halo on the reaction dynamics. Owing to the very low binding energy, n-halo induced reactions exhibit very large total reaction cross-section. An important reaction process in collisions induced by n-halo nuclei is the break-up. At energies well above the Coulomb barrier a large fraction of the total reaction cross-section is due to break-up. At these energies nuclear and Coulomb break-up have been studied in great detail both experimentally and theoretically and we have now a quite good understanding of the process [10].
At low energies, close to the Coulomb barrier, coupling effects dominate the reaction dynamics. Since the ground state of halo nuclei lies very close to the continuum, coupling with the continuum (break-up) may affect the various reaction processes.
Low energy elastic scattering induced by n-halo nuclei shows a suppression of the elastic cross-section in the Coulomb-nuclear interference region [e.g. 11,12]. With the ^{6}He nucleus such a suppression is observed only in collisions induced on high charge targets and is mainly due to the coupling with the low-lying E1 strength in the continuum. The recent results of our ^{11}Be experiment performed at Rex-ISOLDE, have shown a strong suppression of the Coulomb-nuclear interference with a low charge target showing that nuclear as well as Coulomb effects are important at large impact parameters in collisions induced by halo nuclei [12].
The total-reaction cross-section measured for n-halo induced reactions is much larger than the one observed in reactions induced by the corresponding well bound isotope, at similar E_{cm} [12,13,14]. Moreover, from inclusive experiments, it has been observed that a large fraction of the total reaction cross-section is due to direct processes such as break-up or transfer [13,14,15]. Inclusive experiments, however, do not allow to discriminate among the two processes, to this aim complex exclusive experiments, where coincidences between neutrons, gammas and the charged core have been performed. The relative contribution of transfer and breakup has been clearly separated in the systems ^{6}He+^{209}Bi and ^{6}He+^{65}Cu showing that at low bombarding energy transfer rather than break-up is the most important contribution to the direct reaction cross-section [16,17].

1.3 p-halo induced reactions

Contrary to n-halo induced reactions, p-halo collisions are not well studied. Many of the investigations performed with ^{8}B beams concern Coulomb dissociation at energies well above the Coulomb barrier in order to get indirect information on the radioactive capture reaction ^{7}Be(p,γ) of great astrophysical interest for the understanding of the neutrino flux from the sun [18].
P-halo induced reactions may behave differently than n-halo induced collisions. In Coulomb dissociation processes of proton-rich nuclei the loosely bound valence protons participate actively in the reaction process. Due to the dynamic polarization effect the valence proton is expected to be

displaced behind the nuclear core and shielded from the target. This effect causes a reduction of breakup probability compared to first-order perturbation theory predictions and higher-order corrections are required [e.g. 19,20]. As discussed in [21], nuclear processes are expected to have a primary role in the dissociation of ^{8}B. This has been experimentally observed in e.g. ^{8}B+^{208}Pb at 142 A MeV; it was found that the nuclear break-up accounts for about half of the total break-up cross-section [2]. Conversely for ^{11}Be on the same target at a similar energy the Coulomb contribution far exceed the nuclear one [22]. If the electromagnetic coupling is not the dominant contribution to the break-up of ^{8}B, this has important consequences on the conclusions drawn about the interference of E1, M1 and E2 processes and on the extraction of the p-capture reaction rate of astrophysical interest from Coulomb dissociation experiments.

In n-halo nuclei the Coulomb break-up originates from an effective repulsive force acting on the neutron due to the core-target Coulomb potential. In the case of a p-halo, the Coulomb interaction acts also between the *p* and the core and the *p* and the target. In [22] the role of the p–core and p-target interaction in the p-halo break-up is studied theoretically. The effect of these additional potentials is to create an effective barrier which makes the proton of the halo effectively more bound. Due to this, some features in the break-up of p-halo nuclei are expected to be different than in the breakup of n-halo nuclei and, as mentioned above, the nuclear break-up could be comparable or larger than the Coulomb break-up depending on the target charge. This behavior could explain the apparent discrepancy in the interpretation of the different experiments in terms of halo structure of ^{8}B.

At energies around the Coulomb barrier very few data exist. The ^{8}B break-up on a ^{58}Ni target was measured in [23,24] using the in-flight separated "cocktail" ^{8}B, ^{7}Be, ^{6}Li beam produced at the TwinSOL facility of Notre Dame. In order to reproduce the measured ^{7}Be angular distribution an extended p-halo structure of ^{8}B was considered in the Continuum Discretised Coupled Channel Calculations (CDCC). Coulomb-nuclear interference effects were found to be important even at very large distances. In this work, however, it was not possible to separate the contribution of absorption (transfer) and diffraction break-up since inclusive data were measured. The elastic scattering angular distribution was measured by the same authors [4]. The angular distribution was obtained with a limited number of measured angles and with a poor angular resolution. A large total reaction cross-section was extracted from the elastic scattering data, a result similar to what found in n-halo reactions [4].

Keeley et al. [25] performed Coupled Reaction Channel (CRC) and CDCC calculations to evaluate the separate effect of transfer and break-up couplings on elastic scattering for the ^{8}B+^{208}Pb reaction. Both coupling effects were found to be negligible despite the large calculated break-up cross-section. Moreover, according to [25], the transfer cross-section is expected to be small due to the fact that the proton has to overcome a barrier in order to be transferred, opposite to what observed in n-halo induced collisions.

Therefore once again, we notice that different experiments/calculations seem to arrive to conflicting conclusions.

2. Proposed experiment

The successful ^{9,10,11}Be+^{64}Zn experiment that we performed at Rex-Isolde and LNS [12], evidenced how low energy reactions are sensitive to the peculiar structure of the colliding nuclei. In particular, from the comparison between ^{11}Be and ^{9}Be induced reaction one could directly see the striking differences between the reaction induced by a weakly-bound nucleus with a halo (^{11}Be) and a weakly-bound nucleus with no halo (^{9}Be). Moreover it was possible to derive information on the decay length of the neutron wave function inside the halo nucleus.

In order to investigate further the reaction dynamics of p-halo nuclei induced collisions, we propose the development of a ^{8}B beam at Rex-Isolde. The aim of the research proposed here would be to perform the measurement of a detailed elastic scattering angular distribution of the ^{8}B nucleus in the

angular range $15°\leq\theta_{cm}\leq140°$ at 3 degree step and to measure transfer and break-up cross-sections. To this aim we propose to measure ^{7}Be-protons coincidences. Also, in the present case, as in the ^{11}Be experiment, we propose to measure the reaction induced by the weakly bound ^{7}Be, core of ^{8}B.
With the energy presently available at Rex-Isolde the experiment can be performed on light or medium mass targets but with the increase in energy, which will be available with HIE-Isolde, this study could be extended also to heavy targets.
By measuring elastic scattering, break-up and transfer angular distributions one can pin-down information on the role of the nuclear and Coulomb contribution to the ^{8}B dissociation. In [23] the ^{7}Be angular distribution showed that Coulomb-nuclear interference was acting at very large distance. In the same way the observed dumping of the Coulomb-nuclear interference peak in the elastic scattering angular distribution, particularly evident in the ^{11}Be+^{64}Zn case, originated by nuclear absorption occurring at large impact parameters due to the ^{11}Be halo structure.
The Optical Model analysis of the ^{11}Be+^{64}Zn elastic data showed that a very large surface diffuseness parameter (a_{si}=3.5 fm) is needed in order to reproduce the behavior of the cross-section in the region around the Coulomb-nuclear interference. This large diffuseness is related to the decay length of the neutron initial state wave function inside the halo nucleus [26]. Since elastic scattering is a peripheral process, it probes the wave function tail, therefore, information on the halo structure can be directly inferred from elastic scattering measurement.
As mentioned above, the only measured elastic scattering data using a p-halo nucleus, at energies around the barrier, are from E.F. Aguileira et al. [4]. They measured elastic scattering angular distributions of ^{8}B+^{58}Ni at five different energies. In figure 1 it is shown, in linear scale, the elastic scattering angular distribution at E_{lab}=25.3 MeV from [4] (the data are taken from EXFOR). All other angular distributions in [4] have similar quality.
As it can be seen from the figure, the angular distribution was obtained with a limited number of measured angles. In particular, in the region around the Coulomb-nuclear interference only two or three points, depending on the beam energy, were measured. Moreover the angular resolution was poor. We underline however that our results on ^{11}Be+^{64}Zn [12] elastic scattering have shown that only if precise measurements are performed one can observe structure effects on the elastic scattering angular distribution. It was, in fact, possible to observe the suppression of the elastic cross-section in the Coulomb-nuclear interference region, and the associated enhancement of the total reaction cross-section, thanks to the large number of measured angles and the small $\Delta\theta$ bin covered by each point. Therefore, precise measurements are needed to extract reliably the total reaction cross-section from elastic scattering.

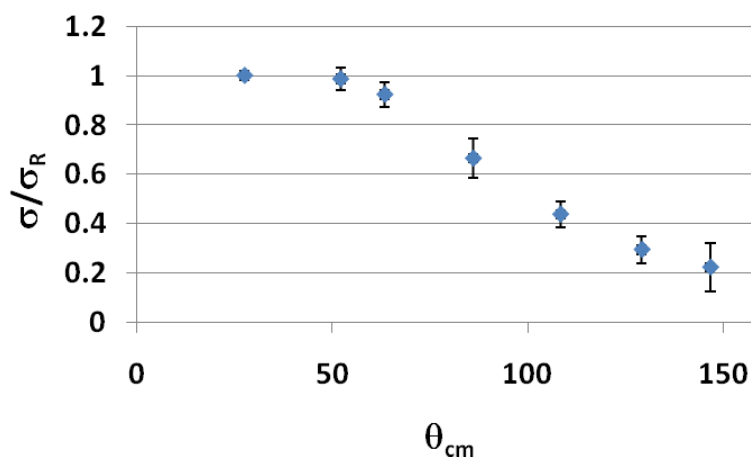

Figure1. Elastic scattering angular distribution of ^{8}B+^{58}Ni at E_{lab}=25.3 MeV [4].

Aim of the present proposal, in addition to the measurement of elastic scattering angular distribution and total reaction cross-section in $^{8}B+^{64}Zn$, is the measurement of the transfer and break-up cross-section by measuring the emitted ^{7}Be particles in coincidences with the protons. Based on energy-momentum matching considerations, the p-transfer will not occur to the ground state of the target nucleus but to an excited state (Q_{gg}=7.32 MeV, Q_{opt}≈-3.5MeV, E_x(65Ga)≈10.8 MeV). Therefore it is expected that the ^{7}Be-p relative energy distribution is narrower for break-up events than it is for transfer. In fig.2 are shown Montecarlo simulations of the energy spectrum of ^{7}Be and p coming from break-up processes. In the simulation it was assumed an excited ^{8}B that would then break-up. The ^{8}B excitation energy distribution was tuned in order to reproduce the ^{7}Be spectrum measured in [24]. With the experimental set-up proposed in the following the efficiency to detect ^{7}Be-p coincidences coming from break-up is ≈70%. This value takes into consideration the detection thresholds.

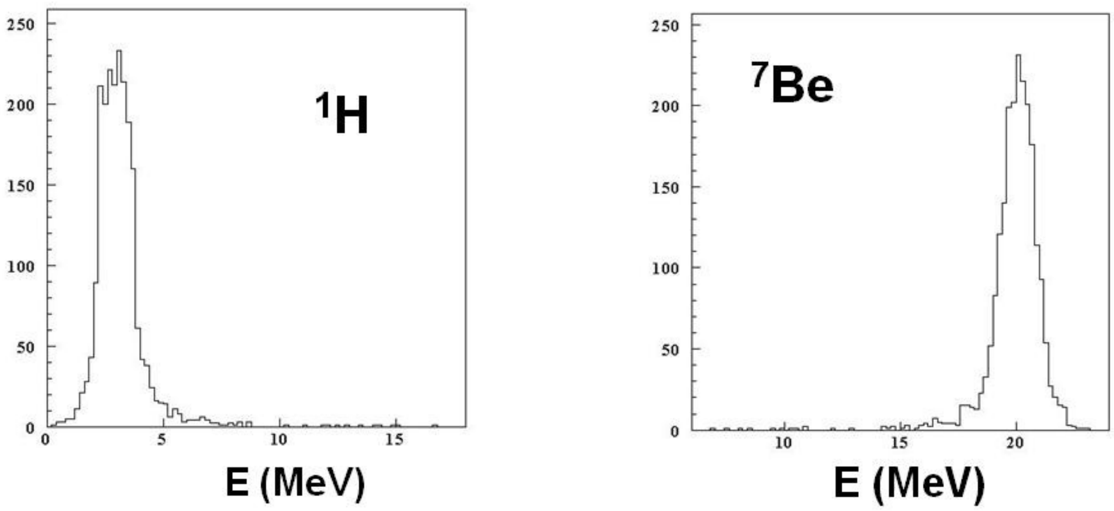

Figure 2. Simulated p and ^{7}Be energy spectra produced in break-up processes.

3. Experimental set-up.

The proposed experimental set-up is similar to the one used for the $^{11}Be+^{64}Zn$ IS438 experiment, sketched in fig.3 [12]. The estimates were done for a ^{8}B beam energy of 3.1 MeV/u, the maximum available energy at REX-Isolde and a target of ^{64}Zn. The choice of ^{64}Zn as a target is due to the fact that on this target we have measured elastic scattering and reactions with halo (^{6}He,^{11}Be) and weakly-bound ($^{6,7}Li$,^{9}Be) beams so we have already a wide systematic.

A target of 1mg/cm^2 will be surrounded by four Si detector telescopes and two 40 μm DSSsD detectors (divided into 16+16 strips). These two last detectors will be placed at backward angles (θ_{cm}>110°). Each telescope will be composed by a 20 μm ΔE Si strip detector (50x50 mm^2 divided into 16 strips) and a 500 or 1000 μm residual energy DSSsD detector (50x50 mm^2 divided into 16+16 strips). With this set-up the angular range 15°≤θ_{cm}≤140° can be covered. With the proposed detection system we aim to measure the elastic scattering angular distribution at 3 degree steps. It will be possible to charge identify the scattered ^{8}B particles up to θ_{cm}≈110°. At very backward angles the energy of the scattered

Figure 3. Sketch of the experimental set-up used in the IS438 experiment [12].

^{8}B particles will not be sufficient to punch trough the 20 μm ΔE detector. We expect that at backward angles the only particles reaching the detectors are H, He and B. Although at θ_{cm}>110° we will not be able to identify neither in mass nor in charge, using 40 μm detectors we expect to obtain a clean B spectrum in the region from 13 MeV to 16 MeV, where the elastic scattering is expected to contribute. The maximum energy deposited by H and He in 40 μm Si is, in fact, 1.8 MeV and 7 MeV respectively. The target will be tilted at 45° with respect to the beam axis in order to allow measuring also at angles around 90°.

4. Estimate of beam time request.

For the estimate of beam time we assumed an average ^{8}B intensity of $5x10^{3}$ pps. As above mentioned we aim at measuring the angular distribution at 3° steps at least in the angular region up to 110°. At backward angles a 5° step will be used. With the proposed geometry we will be able to measure in 21 shifts the angular distribution in the range $15° \leq \theta_{cm} \leq 60°$ with a statistical error from 0.2% to 4%. Concerning the ^{7}Be-p coincidences, it has been estimated that in the requested BTU, a total of ≈500 coincidences will be collected. ^{7}Be-p break-up events will be concentrated in the forward detector, allowing the measurement of the angular distribution.
The ^{7}Be+^{64}Zn elastic scattering will be measured as well in order to get information on the core-target optical potentials. According to the production yield available on the Isolde web, ^{7}Be should have an intensity similar to the ^{10}Be beam, i.e. 10^{7} pps on the target of the experiment, intensity that was achieved in our previous ^{10}Be experiment [12].

5. Conclusions

In conclusion, we would like to point out that a post accelerated ^{8}B beam is not available in any other ISOL facility worldwide. To have such a beam at ISOLDE will certainly be of interest for many other groups. With the present proposal, interesting information about ^{8}B structure effects on reaction mechanisms can be obtained even if a very low intensity ^{8}B beam will be obtained.

6. International competition.

To our knowledge proposals have been submitted at RI Beam factory at RIKEN to develop a low energy in-flight ^{8}B beam for studying elastic scattering and a LoI has been submitted by an international collaboration to develop a ^{8}B beam at the future low energy re-accelerated beam facility of NSCL at MSU in order to study reaction mechanisms with halo nuclei.

7. References

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