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Spallation reactions studied with 4π-detector arrays

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Abstract. Recently there has been a renewed interest in the study of spallation reactions in basic nuclear physics as well as in potential applications. Spallation reactions induced by light projectiles (protons, antiprotons, pions, etc.) in the GeV range allow the formation of hot nuclei which do not suffer the collective excitations (compression, rotation, deformation) unavoidable when using massive projectiles. Such nuclei provide an ideal testbench for probing their decay as a function of excitation energy. In these investigations, 4π-detector arrays for charged particles and neutrons play a major role in the event-by-event sorting according to the excitation energy of the nucleus.

Spallation reactions induced on heavy nuclei allow the conversion of the incident GeV proton into several tens of evaporated neutrons. The neutron production in thick targets has been investigated in great detail thanks to the use of high efficiency neutron detector arrays. When scattered on samples of inert or biological materials, these neutrons can be used to study details of the material structure. They could also be utilized for the transmutation of long-lived nuclear wastes or for the feeding of sub-critical nuclear reactors.

The role of different types of multi-detector arrays is highlighted in this paper. Several references are also given for different uses of high efficiency neutron detectors in other contexts.

Keywords. Spallation reactions; hot nuclei; neutron production; multi-detector arrays.

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1. Introduction

The study of spallation reactions with light projectiles such as protons [1–3], ^{3}He [4], antiprotons [5–9] or mesons [10] has been recently given a strong impetus for two main reasons. First, it has been understood that such reactions were quite effective in bringing nuclei to a broad distribution of excitation energies – essentially of thermal origin – without modifying notably their nucleonic composition. Thus the heated nuclei do not feel the strong collective excitations as they would if they were obtained in collisions between massive nuclei. Moreover, due to the singleness of the massive nucleus involved in the collision, the experimental investigation is quite unambiguous: all emitted particles arise from a unique nucleus and not from several nuclei like in heavy nucleus–nucleus collisions (it is worth stressing that in a nucleus-nucleus collision at several tens of MeV/nucleon there are at least three potential emitters: the projectile-like and target-like nuclei, and the overlapping zone- or neck-built up with part of projectile- and target-nuclei). Spallation reactions induced with light projectiles thus offer a unique testing bench for the investigation of nuclei brought to high temperatures [3]. In particular they allow to investigate to which extent the well-known sequential, statistical model developed in the early days of nuclear physics works at higher and higher temperatures. Also, for the first time, fission induced at low spins can be investigated in great detail in a very broad range of temperatures (a few MeV $\leq E^* \leq 1000$ MeV) [7,8].

In addition to their own interest as a tool to heat up nuclei and thus as a tool for basic nuclear research, the spallation reactions are raising attraction for all their possible applications. The best known are the spallation neutron sources of high intensity (ISIS [11], SINQ [12], ESS [13]), the muon and neutrino factories (e.g. the ISIS facility at Rutherford Appleton Laboratory), and the production of radioactive nuclear beams (ISOLDE at CERN, Switzerland, ISAC at TRIUMPH, Canada). Recently, new promising applications of high-intensity neutron spallation sources have been considered for transmuting nuclear wastes and/or for developing a new type of sub-critical nuclear reactor [15,16]. This has triggered new and systematic investigations of neutron production in thick target of heavy materials under the impact of various hadrons in a broad range of bombarding energies [17–20].

2. Spallation reactions as a tool to excite nuclei in a broad energy domain

When impinging on a nucleus, a GeV proton can deposit part of its kinetic energy by successive nucleon–nucleon interactions. Indeed at such an energy, the De Broglie wave length of the incident proton is relatively small as compared to the mean distance separating the nucleons inside the nucleus and the impinging nucleon does not 'see' the nucleus a whole but as an assembly of individual nucleons bound together by their mean field. This is the basic assumption on which the so-called intra-nuclear cascade (INC) models are generally built. The scattered nucleons can either be directly ejected from the nucleus or behave as secondary projectiles and develop, on their own, nucleon–nucleon collisions inside the nucleus. In the models the elastic and inelastic nucleon–nucleon channels are considered with their respective cross sections as measured in free nucleon–nucleon scattering. In particular the excited states of the nucleon (e.g. the Δ resonance) are considered as transient particles which also contribute to the cascade. When followed as a function of time, as in the model developed by Cugnon [21–23], it can be shown that after a certain amount of time (from 20 to 30 fm/c) the nucleus behaves as a thermally equilibrated nucleus. Due to the Fermi motion and the variety of involved nucleon–nucleon or meson–nucleon reaction channels, the nucleus is left with a broad distribution of excitation energies even when taking into consideration a single impact parameter. This distribution is further broadened when considering all impact parameters since the cascade develops more and more, on the average, as the impact parameter decreases. As a consequence, after the INC, one is left with a variety of nuclei characterized by their charge Z, mass A, excitation energy E^*, spin J. As shown from the results of Monte Carlo simulations [2] the Z and A distributions are pretty narrow (about $3Z$ units FWHM and 8 mass units FWHM for 2 GeV projectiles) and centered only a few Z and A units below those of the target nucleus. In contrast, the E^* distribution is pretty broad extending from a few MeV up to 1 GeV, with the highest excitation energies for the nuclei the farthest removed (in A and Z) from the target nucleus. It is interesting to see whether the decay of the highly excited nuclei still proceeds by a succession of evaporation/fission as it does at moderate E^* or if new phenomena such as a simultaneous multifragmentation process do show up. It is also the first time that the fission process can be investigated at high excitation energies with *weak* spins [2,7,8].

Indeed, fission at high E^* has been investigated so far mainly following heavy nucleus–nucleus collisions, either in fusion reactions or following deeply inelastic reactions [24–29] but in both cases with rather high spins involved.

Before going further into the investigation of highly excited nuclei it is worth presenting the heating process following an antiproton interaction with a nucleus. When the antiproton hits the target nucleus with a fairly small energy (fraction of one MeV) one first forms an antiprotonic atom with the antiproton further cascading down from the outer to the inner shells of the atom where the annihilation eventually occurs. Thus, the annihilation takes place on the outskirts of the nucleus. In most cases, five pions are emitted with a total linear momentum close to 0 (due to momentum conservation) and, as a consequence of the annihilation at a large nuclear radius, only a fraction of the 5 pions interact with the nucleus and can only moderately heat it up [30]. In contrast, when utilizing GeV antiprotons, although the annihilation here still remains essentially a surface phenomenon (due to the large annihilation cross section), the momentum of the antiproton is shared by the pions, thus driving them forward and giving them a better chance to interact with the nucleus. As a consequence much more energy can be deposited into a nucleus than when the annihilation occurs at rest [5,8].

Although differing in their initial stages, the heating up of nuclei with either GeV protons or GeV antiprotons happens to be quite similar, both leading to nuclei with little spin, broad E^* distributions and a population of heated nuclei in A and Z relatively narrow and slightly shifted downward with respect to the target nucleus A and Z. Due to the nearly 2 GeV annihilation energy, the antiproton does not need to be as energetic as the proton in order to bring the target–nucleus to a similar E^* distribution. Preliminary data indicate that a 1.2 GeV antiproton and a 2.5 GeV proton have rather similar average heating effects when impinging on a heavy target nucleus like Au [31].

A study of the decay pattern of nuclei heated up in spallation reactions requires a sorting of the events as a function of E^*. For this purpose, very powerful detection means are needed in order to register as many decay particles as possible on an event-per-event basis. Some years ago, one relied on the number of evaporated neutrons, only, in order to infer E^* [2]. Based on the predictions of an evaporation code, it is indeed shown that for heavy target-nuclei, neutron evaporation is enhanced simply because of the large Coulomb barrier effect suffered by charged particles [32]. However if the neutron multiplicity is a sensitive observable of E^* at low or moderate excitation energies, it progressively looses its sensitivity for increasing E^* when the relative share of evaporated charged particles increases. This has been nicely shown by Goldenbaum *et al* [5]. Above E^* about 450 MeV for a Au target nucleus, multiplicity of evaporated charged particles becomes even more sensitive to determine E^* than measuring the neutron multiplicity only. Therefore, in order to have a good grasp on E^* in a very broad domain (from a few MeV up to 1 GeV), one needs to detect both evaporated charged particles and neutrons with good efficiencies. As shown by Goldenbaum *et al*, E^* can be simply inferred with a good accuracy from the multiplicities of evaporated neutrons and charged particles.

The evaporated neutrons, emitted from a source close to rest i.e. neutrons with a kinetic energy $E < 10$ MeV are best detected using, 4π, high-efficiency, liquid scintillator detectors loaded with Gd [33]. The response functions of such a detector is fairly well understood [34] and efficiency checks can be performed using, for instance, the $\langle E \rangle = 2.1$ MeV neutrons from a Cf source. Typical detection efficiencies for such neutrons are 80–85%, depending on the detection threshold. The additional advantage of such detectors lies in the rapid decrease in detection efficiency with increasing kinetic energy of the neutrons which makes them almost insensitive to high energy neutrons. Thus they are naturally best suited to select those neutrons of interest for determining E^*, i.e. the low energy evaporated neutrons. The detector need not be segmented into a large number of individual cells in order to measure high neutron multiplicities. Indeed due to long diffusion times of neutrons before radiative capture by Gd, these captures are well separated in time allowing a simple counting of the light flashes succeeding the Gd captures in order to obtain the neutron multiplicity. However and as shown in ref. [2,8], a longitudinal segmentation of the detector can be useful in order to infer the angular distribution of the emitted neutrons. The main drawback of Gd loaded neutron detectors lies in the absence of linear momentum characterization for each detected neutron. Nonetheless, in spallation reactions, the connection between the actual evaporated neutron multiplicity and the measured one (evaporated neutrons and neutrons from the cascade) can be established after simulation of the whole process [31].

The measurement of charged particles with multiplicities up to 20–30 requires the development of multi-detector arrays with a good granularity and the coverage of the 4π solid angle with a maximum efficiency. This has been achieved for instance when using the Berlin Si ball developed at HMI Berlin. It is made of 162 adjacent Si diodes (500 μm thick) making up a sphere by tiling 12 regular pentagons, 30 regular hexagons and two types of 120 irregular hexagons [35]. Taking into account the 2 detectors removed to let the beam in and out and the 2 others for the target ladder in and out and considering the target shadowing, it is remarkable to reach a detection efficiency larger than 80% for light charged particles. By pulse shape analysis and TOF measurements it is possible to distinguish between all types of charged particles: light ones, intermediate mass fragments, fission fragments and even evaporation residues if the target is thin enough.

Making coincident measurements with high efficiency $(> 80\%)$ of light charged particles *and* neutrons, most of evaporative origin, one can get access to E^* on an event-per-event basis with a resolution better than 20% (FWHM). In spallation reactions induced on heavy targets, like Au or U, for which the E^* distribution is very broad, the knowledge of E^* is quite indispensable for studying the fate of the excited nucleus. It can end up as an evaporation residue or undergo fission as shown in previous experiments, with E^* strongly influencing its fate [7,8]. In the case of light- or medium-mass target nuclei, the energy deposition can be high enough to blow up- or vaporize- the nucleus in elementary constituents, all with masses equal or smaller than 4 [6].

3. Spallation neutron sources and their applications

The application of spallation reactions to produce high neutron fluxes is already in use for more than a decade at the ISIS facility at Rutherford Appleton Laboratory with a 160 KW proton beam impinging on a heavy target material. Ambitious plans are considered all over the world to build facilities in the MW range in order to boost further the neutron flux. This is of great interest since such sources can be easily pulsed with the proton beam frequency (generally μs bursts with a frequency of several tens of Hertz). This type of facility opens up many more applications than currently possible from high flux nuclear reactors which deliver steady neutron fluxes. With pulsed sources, time of flight techniques become possible allowing the use of white neutron spectra and also making possible the structural and dynamical studies of matter (condensed matter, biological sciences, advanced materials...). In Europe there are projects to upgrade ISIS [11] and to build new sources such as the Austrian project, AUSTRON [36], or the European spallation source (ESS) [13] project. There also exist a National spallation neutron source project (NSNS) [14] under construction in the USA and a joint JAIRI-KEK [37,38] project in Japan. All these projects have triggered new studies [17–20] for neutron production in thick targets with systematic measurements performed with different types of projectiles in a broad range of energies on several materials. Also different shapes of the thick targets have been investigated in order to optimize the neutron production.

To our knowledge it is the first time that in spallation reactions not only the average neutron production is measured but also the second moment of the distribution. This more complete information is very useful to test more thoroughly the different models of neutron production. To perform such measurements 4π, Gd loaded liquid scintillator detectors are very well suited and details can be found in recent publications [17–20]. It has been shown that the neutron production in thick targets does not depend very much on the nature of the used projectile (proton, deuteron, antiproton, pion, kaon) but more on the available energy [17]. At first, this result looks somewhat surprising, but whatever be the nature of the projectile, different types of hadrons and mesons are implied in the inter-nuclear cascades in a very intricate way, leading to several excited nuclei per incident projectile. Thus, there might be some averaging effect over this complicated process. It may also indicate some energy conservation effect although most of the energy is dissipated into electronic heating of the target. Indeed, according to the experimental data about 30 MeV are needed to produce each neutron in spallation reactions in thick targets when only about 10–12 MeV are strictly required to extract a neutron from a heavy nucleus (i.e. its binding energy plus twice the temperature of the emitting nucleus). About 2/3 of the initial projectile energy is thus ‘lost’ for neutron production and finally found as thermal energy in the target material.

4. Concluding remarks

The PMDA-2000 workshop was focused on Physics with multi detector arrays. Through the study of spallation reactions we have demonstrated the needs of very efficient detector arrays for both neutron and charged particles. It can be stressed that the same detector arrays – or similar ones – have been also utilized in many different subfields of nuclear physics when the knowledge of excitation energy is required in order to characterize the different reaction channels. This is true for heavy-ion reactions studied in a broad energy domain (from several MeV/nucleon up to hundreds of MeV/nucleon). Such detectors have also shown to be very useful in the study of nuclear reactions for which there is a strong interplay between nuclear structure and reaction mechanism. This is the case in reactions involving ^{6}He, a so-called halo nucleus with two very weakly bound valence neutrons [39]. Moreover, a new generation of TOF arrangements and large area neutron detectors have also been designed to complement the set of tools at our disposal [40]. It was not possible in this contribution to present the many facets of nuclear physics investigated with 4π, Gd loaded, neutron multi-detector arrays but detailed illustrations can be found in [33,41–44] for heavy-ion induced reactions.

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