A study of coherent bremsstrahlung and radiative capture

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1. Introduction

1.1 Preface

The subject of this thesis is a combination of at first sight two seemingly unrelated topics, nuclear bremsstrahlung and radiative capture. It will be shown that these topics can be approached with a unified view. In the following sections a brief description of the nature of nuclear bremsstrahlung and of radiative capture will be given. Also, the aims of this thesis and an outline will be presented.

1.2 Nuclear bremsstrahlung

Classically, bremsstrahlung is the radiation emitted whenever a charge is accelerated or decelerated. In this respect, bremsstrahlung should occur in any nuclear scattering.

Nuclear bremsstrahlung as a source of photon production was first suggested in 1949 by Ashkin and Marshak [Ash49] who derived cross sections for nucleon–nucleon and nucleon–nucleus systems at 250 MeV. Although the first nucleon–nucleon bremsstrahlung was already observed in the 60's [Got65, War65], it took until 1985 before nuclear bremsstrahlung from collisions between heavy nuclei was observed [Gro85, Bea85, Gro86]. This observation has led to the question of the reaction mechanism. The bremsstrahlung could either originate from the collective deceleration or acceleration of the colliding nuclei as a whole, referred to as coherent bremsstrahlung, or could be due to the collisions of the individual constituent nucleons of the projectile with those of the target (incoherent bremsstrahlung). Since the earliest experiments, one has learned from the angular distributions and the scaling of the yields with the average number of nucleon–nucleon collisions that the photons are produced incoherently [Nif85, Nif90]. In general, the photon yield is attributed to proton–neutron collisions, since the proton–proton contribution is suppressed (see chapter 2). In the nucleon–nucleon center–of–mass system the energy spectra of the photons have an exponential shape and the slope parameter mainly depends on the beam energy per projectile nucleon and not on the target and projectile combination and the total beam energy. From this one has concluded that the bremsstrahlung is produced mainly in the first encounter between a nucleon from the projectile and target nucleus, respectively, i.e. in a first–chance collision.

In contrast to e.g. mesons, the photons produced in the nucleus–nucleus system do not suffer from absorption inside the nucleus. For this reason they were found to be a clean probe to study reaction dynamics. Dissipation mechanisms in heavy–ion collisions have been studied using the bremsstrahlung photons to signal nucleon–nucleon collisions in the early phase of the reaction [Mar95a, Mar95b, Pol96, Pol96a, Sch96, Sch97].

Conceptually simpler than nucleus–nucleus reactions are proton–nucleus reactions. Early experiments were reported around the same time as the first few–body bremsstrahlung experiments [Wil52, Coh63]. Also for these proton induced reactions the proton–neutron collisions are believed to be the main source of bremsstrahlung photons [Nif90].

In particular at intermediate and high energies (i.e. well above the coulomb barrier but below the π threshold), the bremsstrahlung production in nucleus–nucleus and nucleon–nucleus reactions have been described merely qualitatively. As mentioned before, the description is based on the *ansatz* that bremsstrahlung is produced in incoherent first–chance nucleon–nucleon collisions. An interesting

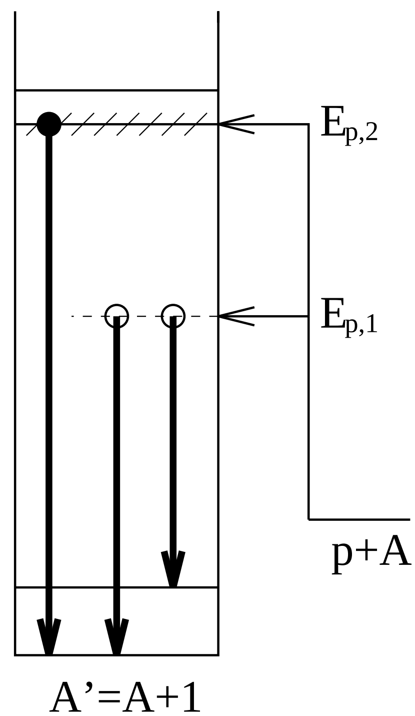

Figure 1.1: Example of direct capture ($E_{p,1}$) and resonant capture ($E_{p,2}$) by a proton.

question is whether collective or coherent bremsstrahlung can be ignored completely. Also the production by first–chance interactions needs to be reconsidered, in particular when the beam energy increases. These questions can be addressed by a judicious choice of the projectile and target combination.

In this thesis the importance of coherent bremsstrahlung is addressed, i.e. the bremsstrahlung originating from the collective deceleration/acceleration of the nuclei as a whole. The studied system is $\alpha + \mathrm{p}$ at 50 MeV/nucleon. In this system, the strongly bound α particle allows a large energy window to study this coherent bremsstrahlung as will be discussed later in this chapter (section 1.5). In other work, the role of 'non–first–chance' collisions has been addressed by Van Goethem [Goe99] by investigating the multiple scattering of the incoming proton for different targets.

The knowledge of the elementary bremsstrahlung process in nucleon–nucleon collisions has improved, although the experiments are difficult. Bremsstrahlung production in few–body systems (p+p, p+n, p+d) has been studied since the 60's [Got65, War65]. The initial hope was that the off–shell scattering matrix could be studied. However, it appeared that these data could be described by soft–photon calculations that do not include off-shell effects (chapter 2). Since the early 90's high precision few–body bremsstrahlung experiments have been set up at various laboratories. The present accuracy is high enough to disentangle possible off–shell contributions and higher order effects [Hui99, Kal98, Mes99, Zlo98]. A clear picture has not yet emerged.

1.3 Direct radiative capture

Radiative capture has been studied extensively, particularly at low energy because it is one of the most important reactions for the formation of elements in the universe. There are many different mechanisms of radiative capture, the most important are direct and resonant capture (see chapter 2).

Simply stated, the direct capture process involves a transition from an initial state describing the relative motion of projectile and target to a final bound, or unbound, state of the nuclear composite. In absence of a matching resonance at the initial–state energy only direct capture can occur (the two transitions from $E_{p,1}$ in figure 1.1). Direct capture is considered in this thesis because of the role of transitions to the ground and first–excited states of ^{5}Li in the $\alpha + \mathrm{p}$ experiment.

The direct radiative capture of protons, deuterons, ^{3}He and ^{4}He on various nuclei is recognized from the fact that the cross section varies slowly with the beam energy. In resonant capture the incident particle is captured into a narrow and thus long–lived resonance, which subsequently can decay via γ–ray emission. To this cross section the direct capture component must still be added [Rol73, and references therein].

One of the earliest reported studies on direct radiative capture was in 1949 by Fowler et al. [Fow49] in a D(p,γ)^{3}He reaction at proton energies of 0.5–1.7 MeV. They showed the slowly varying photon yield as a function of proton energy. The angular distribution of the photons had the shape of a $\sin^2\theta$. Radiative capture has since become a major tool in nuclear structure studies, because detailed angular distributions are sensitive to the structure of the populated states. For example, the observed deviations from the $\sin^2\theta$ dependence in the reaction mechanism above can be used to establish the amount of d–state admixture in the ^{3}He ground state [Kin83].

With increasing beam energy other phenomena start to play a role. In particular if a giant resonance (GR) can be excited, e.g. via inelastic scattering, it can be followed by electromagnetic deexcitation. As the beam energy is increased further more complex states can be formed which preferentially decay with the characteristic GR energy due to the coherent nature of this transition. For the giant dipole resonance this has been observed rather clearly [Dow83]. As the phenomenon has been observed at energies in the range of this work we will discuss it further in the theory chapter. At even higher energies ($E_p \gtrsim 100$ MeV) direct processes prevail, however other degrees of freedom such as Δ excitation of the nucleons must be considered [Bri96]. Such processes are not relevant for the present work and will not be considered further.

1.4 Current understanding of ^{5}Li

As mentioned in the previous section, the γ–ray transitions from the $\alpha + \mathrm{p}$ system will probe the lower–lying and possibly higher–lying states of ^{5}Li . ^{5}Li has been studied in scattering experiments. This information is used to deduce the energy levels in ^{5}Li by the 'extended' R–matrix method [Til98]. The levels are shown in figure 1.2. The (unbound) ground state and first–excited state are both p–states and are very broad, 1.2 and 6.6 MeV, respectively. The level parameters (widths and energy levels) differ significantly from earlier values (e.g. in [Ajz88]), which were obtained from a more standard R–matrix method. However, the 'extended' R–matrix method is recommended for light systems with broad resonances [Til98]. The d–state at 16.87 MeV is very sharp (0.3 MeV) and is the so–called 'fusion resonance', which is of importance in an energy–producing fusion reactor, using the d+^{3}He or d+^{3}H reactions as a fuel, with $E_d \approx 0.45$ MeV. The most important phase shifts of the $\alpha + \mathrm{p}$ system are shown in appendix B (s1/2, p1/2, p3/2 and d3/2). These phase shifts are used in the various theories to calculate photon–production cross sections (see chapter 2).

The reaction ^{3}He$(d, \gamma p \alpha)$ has been measured and interpreted in terms of radiative capture to ^{5}Li [Bus68, Bal91, Bal94]. The photon energy spectra were used to determine the width of the ground state of ^{5}Li experimentally. The values are the result of different fit procedures, obtaining widths between 1.5 and 2.6 MeV. These fits did not include the presence of the first–excited state. As

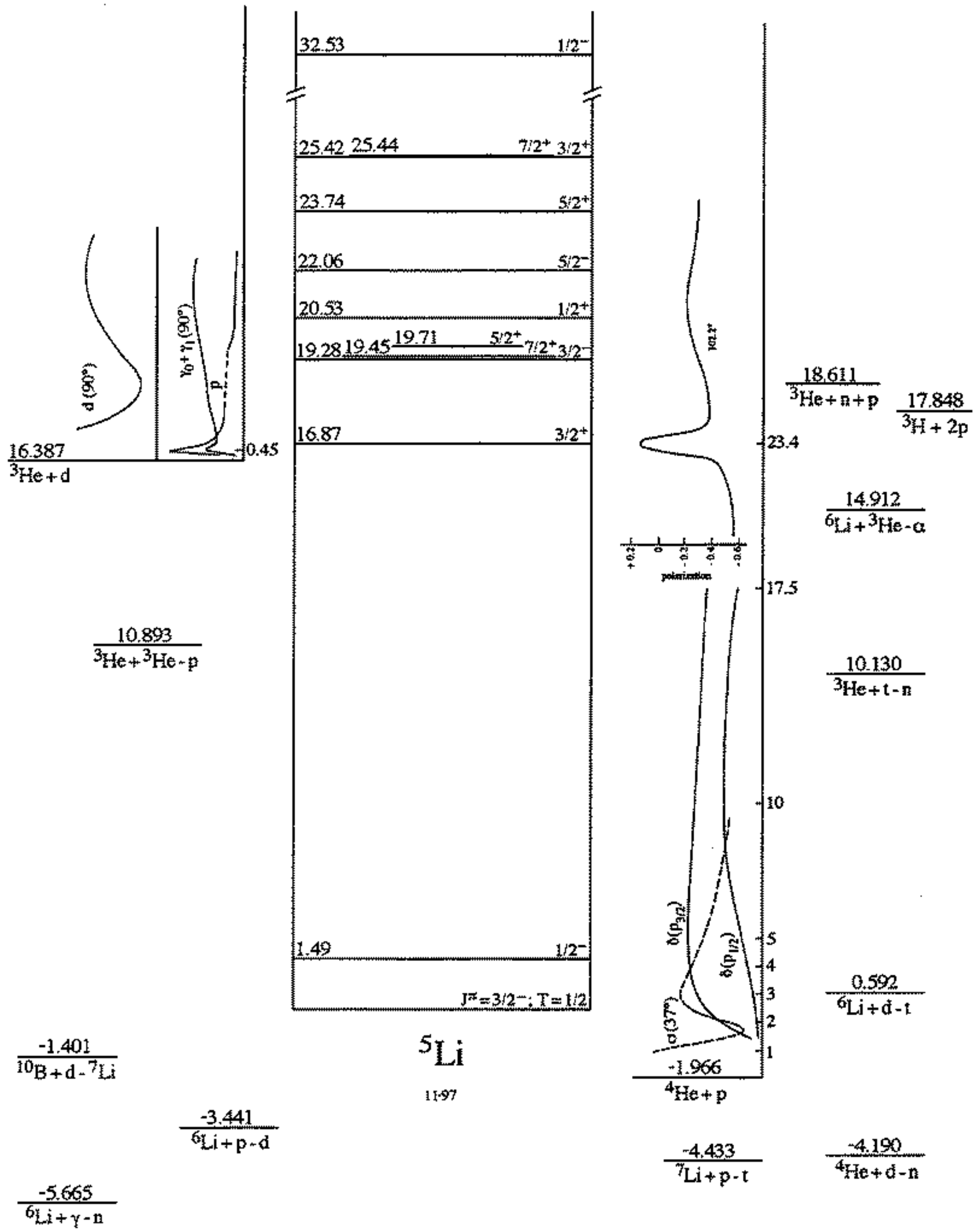

Figure 1.2: Energy levels of ^{5}Li (obtained from [Til98]).

mentioned, a value of 1.2 MeV is quoted as the result of the 'extended' R–matrix method.

Also in the few known $\alpha + \mathrm{p}$ bremsstrahlung experiments, the importance of the resonances in ^{5}Li has been recognized. These experiments have been done in the 70's by measuring α–p coincidences in a fixed geometry for proton energies between 7 and 45 MeV [Wol71, Anz75]. The photons were not detected, but their energies can be obtained from the kinematically complete measurement of the proton and the α–particle. Due to the fixed geometry, only a very small range in photon energy could be extracted indirectly from the data. These photon energies did not probe the ^{5}Li ground state. However, it was found that bremsstrahlung calculations along the lines of Low [Low58] were not sufficient to describe the few data points. The final–state interaction, as described by the phase shift corresponding to the energy of the $\mathrm{p} + \alpha$ system in the exit channel, needs to be taken into account. Calculations along the lines of Feshbach and Yennie, including

a)

b)

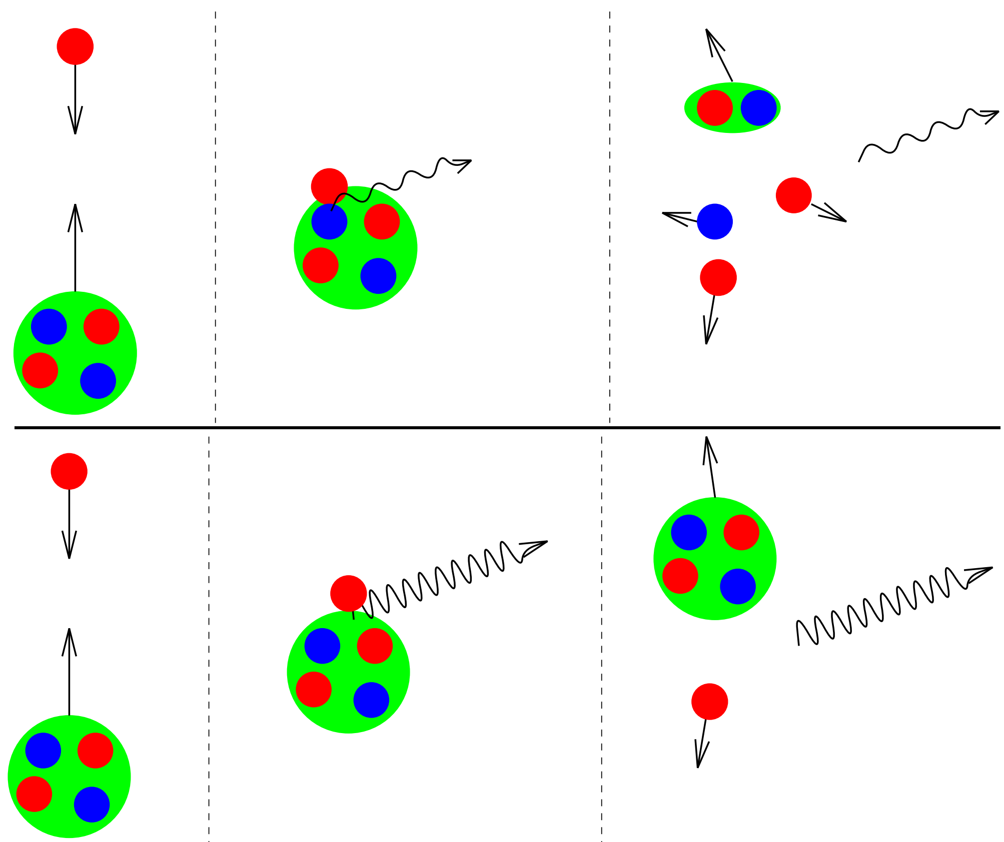

Figure 1.3: Cartoon of $\alpha + \mathrm{p}$ process: a) In case of the break–up of the α: $E_\gamma < 20$ MeV. b) In case of 'coherent' bremsstrahlung: $E_\gamma < 39$ MeV.

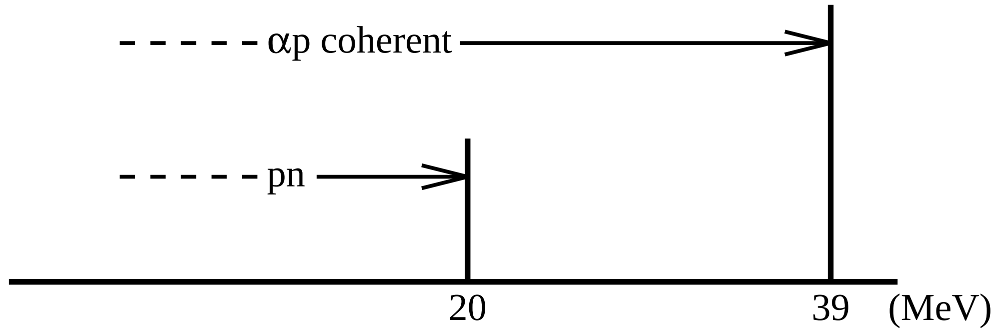

Figure 1.4: Kinematic limits for photons produced coherently or incoherently in $\alpha + \mathrm{p}$ at 50 MeV/nucleon.

the final–state interaction, have been used to describe the data [Fes62, Gre72].

1.5 This work

As has been established in intermediate–energy heavy–ion collisions (section 1.2), the most important contribution to bremsstrahlung originates from quasi–free proton–neutron collisions in the nuclear medium. However, the question whether significant nuclear bremsstrahlung can be produced in a coherent manner has not been answered yet unambiguously. The $\alpha + \mathrm{p}$ system at 50 MeV/nucleon is an interesting system since its kinematics makes it possible to disentangle the two bremsstrahlung production mechanisms, i.e. in quasi–free proton–neutron collisions and in coherent production. For the $\alpha + \mathrm{p}$ system at 50 MeV/nucleon the kinematic limit for *pn* collisions is 20 MeV, as the quasi–free process involves the break-up of the strongly bound α-particle (figures 1.3a and 1.4). Above this threshold energy, all photons have to be produced coherently. That is, the α-particle does not break up, but instead it contributes as a whole to the production of a bremsstrahlung photon (figure 1.3b). The maximum available energy for the bremsstrahlung photons is 39 MeV in this case (figure 1.4).

The $\alpha + \mathrm{p}$ experiment has been performed at *KVI* in the spring of 1997, In this experiment nearly the full double differential cross section $d^2\sigma/(dE_\gamma d\Omega_\gamma)$ was measured. This gives a very complete picture of the reaction, which requires a consistent description concerning bremsstrahlung and radiative capture.

1.6 Outline

Since coherent and incoherent nuclear bremsstrahlung processes as well as capture processes are involved in the interpretation of our data, models of both types are used to compare the data with. In chapter 2 several of these models to calculate cross sections and angular as well as energy distributions are discussed .

The setup of the $\alpha + \mathrm{p}$ experiment involves the Two–Arm Photon Spectrometer *TAPS* and the Small–Angle Large–Acceptance Detector *SALAD*. They will be discussed in chapter 3, together with two large pieces of *KVI*–instrumentation for general use with which the author was particularly involved: the *Carbon–Fibre Scattering Chamber* and the *Forward Wall*. The *Carbon–Fibre Scattering Chamber* has been used also as the scattering chamber of the $\alpha + \mathrm{p}$ experiment. For the *Forward Wall* some recent results are presented.

The analysis of the $\alpha + \mathrm{p}$ data, involving a *TAPS* and *SALAD* analysis, is discussed in chapter 4. The general results of the $\alpha + \mathrm{p}$ experiment as well as the comparison with theory are discussed in chapter 5. Conclusions and an outlook are given in chapter 6.