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NUCLEAR BREMSSTRAHLUNG IN PROTON INDUCED REACTIONS AT 190 MeV (FIRST EXPERIMENTS AT AGOR)*

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An overview is given of the first experiments with the new KVI cyclotron AGOR. First experiments have focused on nuclear bremsstrahlung in few– and many–body reactions. A classical introduction to nuclear bremsstrahlung is given. First results on coherent bremsstrahlung are discussed.

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1. Introduction

Nuclear Bremsstrahlung provides an important means to study nuclear systems. It can be applied in such distinct fields as few–body and many–body nuclear physics. In the first case it is used to study the off–shell behaviour in nucleon–nucleon scattering. In the second it provides information about the reaction dynamics. I will describe here in some detail, how this can be done.

Bremsstrahlung studies have been the main theme of research performed with the new cyclotron AGOR (Accelerateur Groningen ORsay) at the KVI, which has been operating approximately for a year now. An important factor for these studies has been the availability of the photon spectrometer of the TAPS collaboration [1] in the same period. Most of the experiments required the maximum proton beam energy of AGOR which is 195 MeV, thus requesting right away optimal performance. Presently, polarized proton beams of 190 MeV and alpha beams of 200 MeV are readily available.

The outline of this report is as follows. I will first provide the basic concepts concerning nuclear bremsstrahlung and discuss shortly the experimental setup for these studies. Next some preliminary results obtained for

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proton–proton scattering will be discussed, followed by a presentation of proton–nucleus bremsstrahlung. I will conclude with the results of a search for coherent bremsstrahlung in the α–proton system.

2. Concepts of nuclear bremsstrahlung

Whenever a charged particle is accelerated or decelerated, electromagnetic radiation can be emitted. Classically, the differential photon spectrum can be expressed as (see *e.g.* [2])

$$\frac{d^2I}{d\omega d\Omega} = \frac{z^2e^2}{4\pi^2 c}\left|\int \frac{d}{dt}\left[\frac{\vec{n}\times(\vec{n}\times\vec{\beta})}{1-\vec{n}\cdot\vec{\beta}}\right] \mathrm{e}^{i\omega(t-\vec{n}\cdot\vec{r}(t)/c)}dt\right|^2 , \tag{1}$$

where ω is the frequency of the radiation and $\vec{n}$ is the direction of emission. The moving of the charge (ze) is described by its velocity $\vec{\beta}(t)$ and its position $\vec{r}(t)$. If the change in velocity is fast with respect to ω the phase factor can be neglected. This is a good approximation in the case of nucleon–nucleon collisions when the photon energy $E_\gamma = \hbar\omega$ is small compared to the center of mass energy. With this approximation one obtains

$$\frac{d^2I}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c}\left|\sum_k z_k \frac{\vec{n}\times(\vec{n}\times\vec{\beta}_f(k))}{1-\vec{n}\cdot\vec{\beta}_f(k)} - \frac{\vec{n}\times(\vec{n}\times\vec{\beta}_i(k))}{1-\vec{n}\cdot\vec{\beta}_i(k)}\right|^2 . \tag{2}$$

Here k is the index for projectile and target charge assuming that both could be charged particles. It should be noted that these amplitudes are the leading terms in a more comprehensive low energy theorem such as given by Low [3] or Feshbach and Yennie [4]. It is also discussed in the previous talk by Scholten. In nucleus–nucleus collisions the collective stopping is not sufficiently rapid to give an appreciable bremsstrahlung spectrum. Instead one observes the radiation from the much harder in-medium nucleon–nucleon collisions. In this case the sum in equation (2) extends over all constituent charged particles. Their velocities, $\vec{\beta}(k)$, are given by the internal velocity of the Fermi motion coupled to the nucleus–nucleus collision velocity. It is generally assumed that the relative phases of the different collisions are random, *i.e.*, the contributions to the total spectrum add incoherently. Therefore, bremsstrahlung in nucleus–nucleus reactions can be used to monitor the number of nucleon–nucleon collisions, in particular during the early phase of the reaction when the relative velocities are large. This has been the basis for a large number of reaction studies in the recent past [5]. However, the assumption of incoherent in medium collisions does not always hold. In Section 5 and 6 reaction studies concerning coherent bremsstrahlung are discussed. Of a complete different nature is the study of the off-shell behaviour of the nucleon–nucleon interaction. Here it is essential to compare detailed data to precise theoretical calculations. High accuracy is required because the information is masked by the leading orders of the soft photon approximation. In this approximation it is sufficient to know the energy dependence of the on-shell T-matrix obtained from elastic scattering. Models for the nucleon–nucleon interaction are tuned using elastic scattering data, however their off-shell T-matrix may differ. For this reason they the prediction of the bremsstrahlung yields are model dependent, but *not* in leading order.

In both applications of bremsstrahlung one is hampered by the small cross section of this electromagnetic process. These studies require an effective experimental setup to reduce the 'hadronic background' of reaction channels not involving bremsstrahlung.

3. Experimental setup

In the experiments the bremsstrahlung photons are measured using the photon spectrometer of the TAPS collaboration. It consists of approximately 400 BaF_2 crystals of hexagonal shape with an inner diameter of 5.4 cm and a length of 25 cm. Photons will create electromagnetic showers that spread over several crystals which are packed in blocks of 64 modules or in a single large configuration ('supercluster mode'). By summing the energy deposited in the neighboring crystals the incident photon energy is obtained. In the present setup with the crystals in the block mode an angular range of 57° to 176° was covered with a vertical acceptance of 45°. In the supercluster mode the full azimuthal range was covered at polar angles between 130° and 170°. In the block mode veto detectors are mounted in front of each detector to allow a trigger indicating a possible photon event. In addition it can be used to discriminate between photons and electrons. For the study of bremsstrahlung in proton–proton scattering a dedicated detector was build at KVI. This device, the Small Angle Large Acceptance Detector (SALAD) allows to identify inelastic events while rejecting the high intensity of elastic scattering events. It consists of 24 plastic scintillators with a thickness sufficient to stop the inelastic protons while thin enough to let the elastic events through. The latter particles will fire veto scintillators placed behind the energy scintillators. A programmable fast trigger module [6] selects those events in which at least two inelastic protons are seen and a (neutral) event in TAPS. The precise trigger conditions and trigger mix can be obtained using additional programmable units. The angles of the protons are determined in wire chambers in front the scintillators. A schematic view is given in Fig. 1.

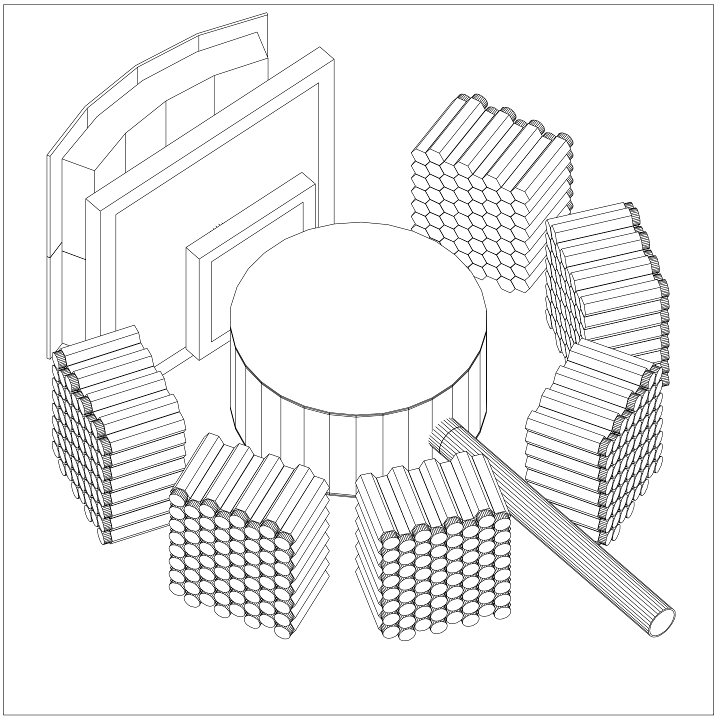

Fig. 1. A schematic view of the setup. TAPS is configured in 6 blocks of 64 BaF_2 modules placed around a carbon–fibre scattering chamber. The square structures at forward angles depict the proton detector SALAD, see also text.

4. The few-body program

Two sets of experiments have been made to study bremsstrahlung in proton–proton and proton–deuteron scattering. The latter mainly to study the proton–neutron scattering, but it also provides information on capture (^{3}He) and on coherent bremsstrahlung off the deuteron. Because the reaction parameters are generally overdetermined background can be effectively eliminated and the reaction channels can be resolved. The experiments have been finished but at this moment only preliminary data are available.

As an example, in Fig. 2 the results are shown for the differential cross section $d^5\sigma/d\Omega_{p_1}d\Omega_{p_2}d\theta_\gamma$ in a coplanar geometry, with one particle fixed at $\theta = 16°$ and with $\theta_\gamma = 145°$. This allows for two different phase space regions with the photon at the same side or opposite side of the first particle. Both possibilities are shown (left and right panel). The dotted lines show the result of a soft photon approximation (SPA) [7], while the full line represents the results of a 'complete' theoretical model by Martinus, Scholten and Tjon [8], which includes higher order terms due to the mesonic degrees of freedom, virtual delta excitation and the $N\bar{N}$ contribution. The dot-dashed calculation is of the same authors but only considers the 'normal' nucleonic bremsstrahlung without these contributions.

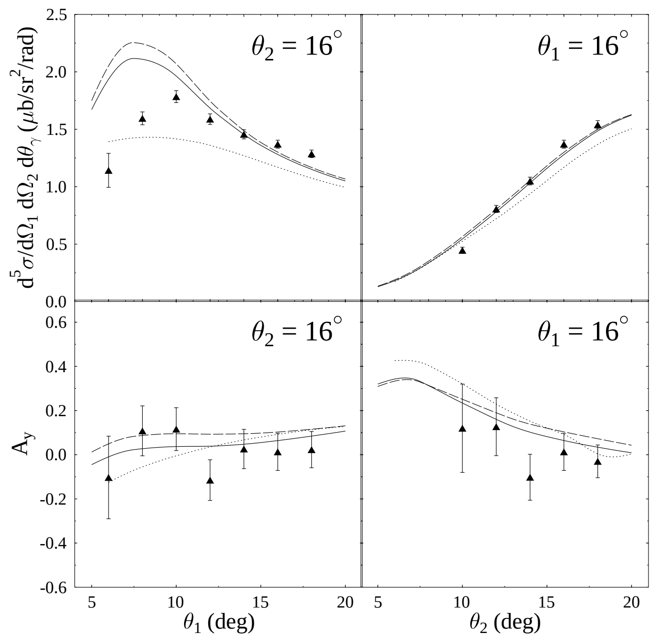

Fig. 2. Preliminary cross sections and analyzing powers as a function of first (left) and second (right) proton polar angles, obtained in the "supercluster" geometry for $\theta_\gamma = 145°$. The second (first) proton angle is fixed at 16°, respectively. The calculations are SPA (dotted), the "nucleonic calculation" (dashed), and the full calculations including MEC, $N\bar{N}$ and the Δ as well (solid).

The small differences between the latter two calculations show why it is important to obtain accurate data if one wants to be able to distinguish between calculations. Whenever, the difference between the complete theory and the SPA is large, one may expect an increased sensitivity to the 'off-shell' information of the data. In this respect the deviation of the data at small angles (top left panel) is surprising and needs further investigation. Another important tool to discriminate between models is the measurement of the analyzing powers (bottom panels). However the statistical errors at this moment are too large to allow for this.

The present setup also provides the possibility to measure a different type of bremsstrahlung, *i.e.*, virtual bremsstrahlung (internal pair creation). Virtual bremsstrahlung carries potentially more information than real bremsstrahlung, due to the increased number of degrees of freedom. A drawback is, of course, the much lower cross section. In addition, the cross section is largest for small photon masses where it carries essentially the same information as normal bremsstrahlung. Moreover, also for virtual bremsstrahlung a low energy theorem dominates the observables. Nonetheless, the data obtained show the viability of such measurements. Preliminary results are shown in Fig. 3 where the cross section as function of the mass of the virtual photon is shown. The calculation is a SPA for virtual bremsstrahlung [9]. The calculation shows the dominance of the transverse component, which at low invariant mass corresponds to 'real' bremsstrahlung. The longitudinal part contains completely new information, not contained in normal bremsstrahlung.

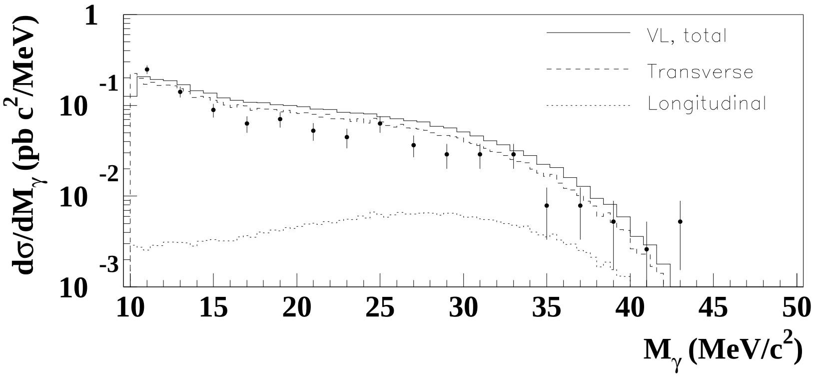

Fig. 3. Preliminary cross section of the virtual proton-proton bremsstrahlung as a function of the invariant mass of the photon. The longitudinal and transverse components of the cross section are separately shown.

5. The proton–nucleus program

Experiments were done to measure the production of photons and neutral pions upto the kinematic limit and to study the modification of the free bremsstrahlung process in the nuclear medium. Measurements were made with polarized protons of 190 MeV on natural targets of C, Ni, Ag and Au. The trigger mix contained γ–γ coincidences to measure and identify neutral pions from their two–photon decay, and particle–γ coincidences which allow one to study the bremsstrahlung process in more detail, as will be shown below. It has indeed been possible to observe the pion and photon spectrum upto the kinematic limit. This is shown in Fig. 4, the photon spectra extends upto $\approx$ 180 MeV. The pion spectrum was obtained by subtracting the

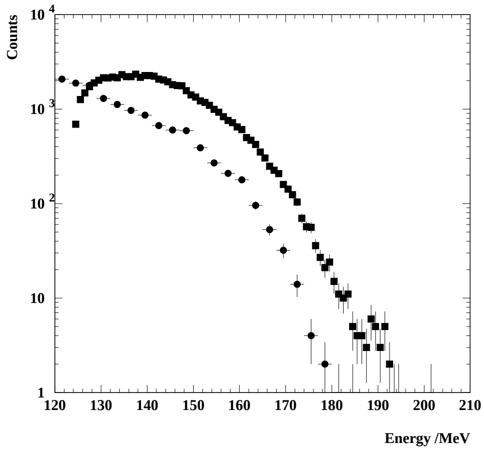

Fig. 4. Preliminary energy spectrum of photons and pions near the kinematic limit in the reaction p+Au at 195 MeV.

experimentally found pion mass from the sum of the photon energies. The spectrum overshoots the limit by about 10 MeV due to this analysis method. In a later analysis this will be corrected for. In this report I would like to concentrate on the exclusive bremsstrahlung measurements which aim to study the role of the medium. One of the interesting effects is due to multiple scattering: When a proton scatters sequentially off two neutrons the bremsstrahlung amplitude associated with both scatterings add coherently. In this case the relative phase from Eq. (1) can not be neglected.

In addition to the amplitudes associated with the incoming and outgoing proton given by Eq. (2) one obtains a third amplitude of similar form but with a phase given by $1 - \mathrm{e}^{i\phi}$ with $\phi = \omega\tau(1 - \vec{n} \cdot \vec{\beta}_m)$, where τ is the time between the two collisions and $\vec{\beta}_m$ is the proton velocity between collisions. The effect of the second collision is than approximately that the bremsstrahlung cross section increases with a factor $4\sin^2(\phi/2)$. With a mean collision time τ_0 given by the mean free path of the proton (≈ 3.3 fm) the average contribution amounts to a factor

$$\frac{2(\omega\tau_0)^2}{1 + (\omega\tau_0)^2}. \tag{3}$$

Therefore, the spectrum at large photon energies increases as if the secondary processes add incoherently, while at low energies there is little additional cross section. This is a very important result as it prevents a hot nucleus from cooling rapidly via 'infrared radiation'. The importance of this result was already realized by Knoll *et al.* [10, 11]. This quenching of low energy photons can be observed in intermediate energy reactions as the quenching factor is 50% at 25 MeV for typical velocities of $\beta \approx 0.3$. To find whether the quenching can be observed experimentally we make use of the fact that quasi-free scattering extends only upto about 90° in the laboratory frame, multiple scattering is required to emit particles at larger angles. In Fig. 5 photon spectra are shown gated on neutral particles observed at various angles in the TAPS spectrometer. The spectra were normalized to each other at energies above 80 MeV. Their is a distinct difference between the spectra which could be interpreted as a quenching effect around 30 MeV. However, there are many other factors that have to be considered before such a claim can be made. In particular, the photons of neutral–pion decay contaminate the spectrum around 60 MeV. Further analysis is in progress.

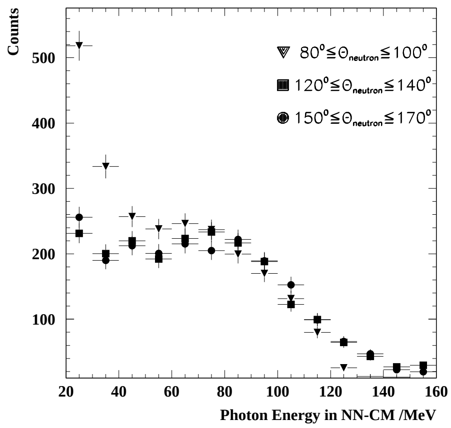

Fig. 5. Preliminary photon spectrum (in the NN-c.m.) gated on different neutron laboratory angles in the reaction p+Ni at 195 MeV. See text.

6. Search for coherent bremsstrahlung in the $\alpha + p$ reaction

A more convetional form of coherent bremsstrahlung occurs when the target remains in its ground state. In the system $p + \alpha$ this coherent bremsstrahlung can be studied conveniently because of the large binding energy of the α-particle. The break–up energy is about 20.6 MeV. In this experiment we used an α-beam of 200 MeV and the same liquid hydrogen target as in the p–p bremsstrahlung experiment. In this case all photons produced with

$E_\gamma > 17$ MeV in the center of mass (c.m.) of the $\alpha + p$ system must be coherent in view of the Q–value of the reaction. Bremsstrahlung studies for this system [12] have been performed before, but only for a few singular points in the total phase space for this reaction. These few data could be described within the low-energy theory (SPA) of Feshbach and Yennie [4]. In the present setup, however, bremsstrahlung can be studied for nearly the full phase space. In a planned experiment at GANIL we want to study the neutron–halo structure of ^{6}He using bremsstrahlung in the $p+^6$He reaction. For this study it is important to obtain the bremsstrahlung contribution associated with the α-core. Thus giving additional motivation for this experiment. So far only the inclusive photon spectrum has been analyzed, which I will report on here.

According to the classical expression of Eq. (2) one would expect a photon spectrum with a $1/E_\gamma$ dependence. However, the spectra we have measured differ completely from this dependence. It shows the highest yield near the kinematic limit for bremsstrahlung. After transformation to the $\alpha+p$ c.m. system a photon spectrum is obtained reminiscent of capture, see Fig. 6. The corresponding angular distribution is shown in Fig. 7 we discuss

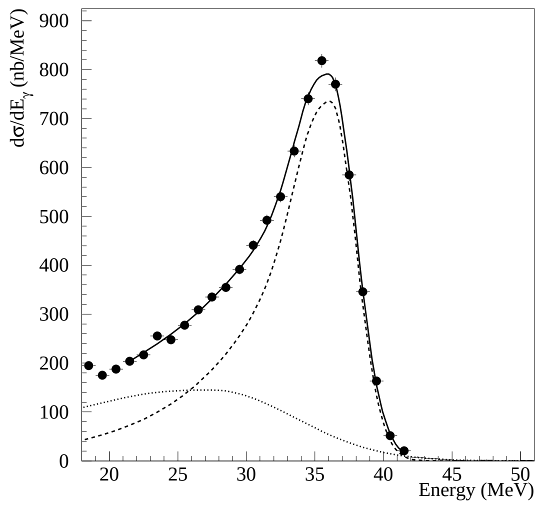

Fig. 6. Photon energy spectrum in the c.m. frame integrated over the spectrometer acceptance. The drawn line is the result of the fit assuming two contributions, given by the dashed and dotted lines, respectively. These contributions can be attributed to the population of the two lowest states of ^{5}Li.

later. Note that ^{5}Li is not particle stable, therefore, strictly speaking, we observe bremsstrahlung. To find if a description in terms of capture is consistent with the spectral shape we fitted two gaussian peaks with variable width and position to the data. The results of this fit are compared with the

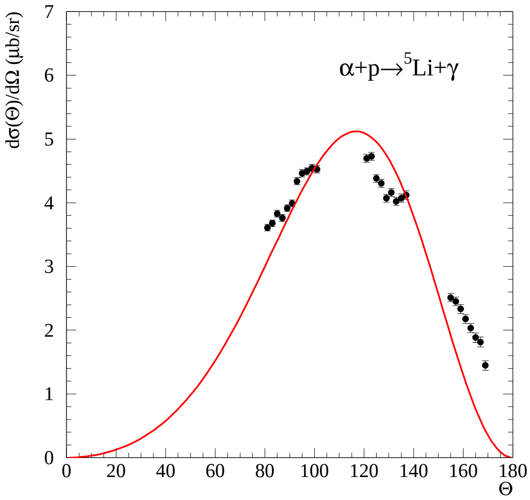

Fig. 7. Angular distribution of photons above $E_\gamma = 22$ MeV in the c.m. The drawn line is given by Eq. (4), normalized to the data.

TABLE I

Deduced parameters of ^{5}Li resonances

	^{5}Li			
	experiment		Ref. [13]	
J^π	E_x	Γ	E_x	Γ
$\frac{3}{2}^-$	–	< 4	0	1.5
$\frac{1}{2}^-$	8.7±0.3	< 15	5–10	5±2
rel. intensity	1.8±0.2		2	

resonance parameters of ^{5}Li in Table I. Considering the resolution of TAPS and the width and positions of the peak, the observed spectrum is indeed consistent with the assumption of capture. We also considered the angular distribution: Using Eq. (2) and taking $\beta_f = 0$ an analytical expression can be obtained for the angular distribution. We find

$$\frac{d\sigma}{d\Omega_\gamma}(1+2 \to 3+\gamma) \propto \frac{(E_1 Z_2 - E_2 Z_1 - (Z_1+Z_2)p\cos\theta)^2}{(E_1E_2 + (E_1-E_2)p\cos\theta - p^2\cos^2\theta)^2}\sin^2\theta, \quad (4)$$

where p is the c.m. momentum and E the energy (mostly the mass) of the particles.

As we have not found this expression in the literature, we compared it with angular distribution for light systems with similar photon energies. Examples are shown in Fig. 8. The agreement confirms that Eq. (4) gives to first order the E1/E2 mixing due to the difference in the charge-to-mass ratio of projectile and target. In Fig. 7 the angular distribution of the photons is shown together with the angular distribution given by Eq. (4). Also here we find the characteristic distribution of capture. On the other hand the total yield predicted using the classical approximation integrated over the appropriate energy range is within a factor 2 of the measurement [18]. In general, the electromagnetic sumrules should be obeyed independent of the production mechanism of the radiation. For this reason it will be interesting to investigate to which extent the low-energy approach of Ref. [4] is applicable and to obtain a quantitative prediction for radiative capture. In principle the coherent bremsstrahlung data can be used to obtain structure information of the ^{5}Li nucleus.

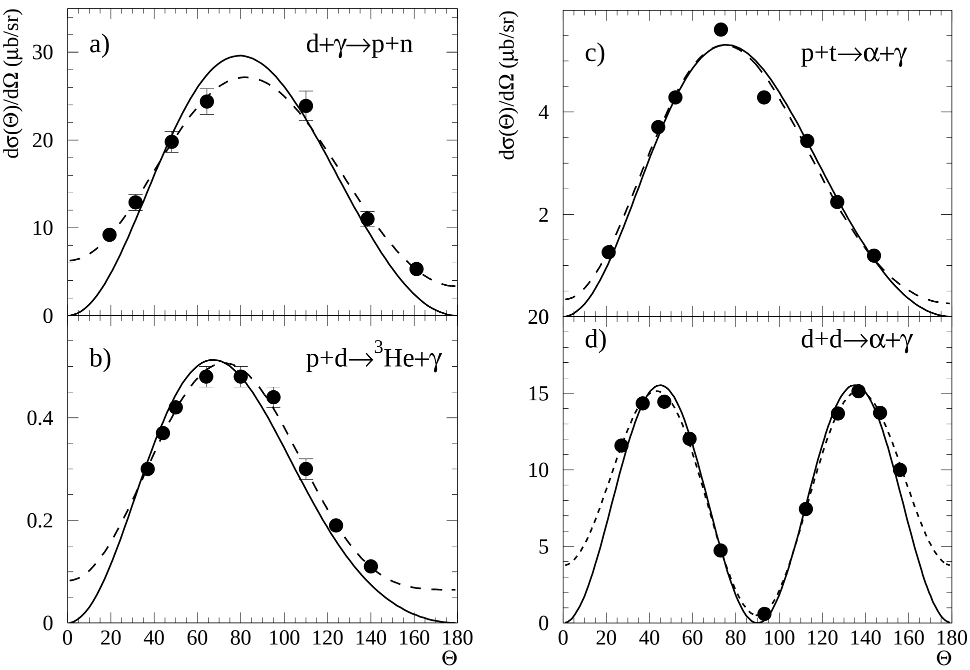

Fig. 8. Angular distributions for various light systems. The dashed lines correspond to a fit with Legendre polynomials (up to 4$^{\text{th}}$ order), the full line Eq. (4) normalized to the data. a) Ref. [14], photodistintegration of the deuteron $< E_\gamma >= 34$ MeV, b) Ref. [15] $p + d$ capture $E_p = 40$ MeV ($E_\gamma = 32$ MeV), c) Ref. [16] $p + t$ capture $E_p = 21$ MeV ($E_\gamma = 35$ MeV), d) Ref. [17] $d + d$ capture $E_d = 10$ MeV ($E_\gamma = 28$ MeV).

The work described here is a joined effort of the TAPS collaboration and the KVI (SALAD). We are greatly indebted to the AGOR team for their continuous efforts to produce quality beams in the developing phase of the new cyclotron. The results shown in this report are due to the analysis efforts of L. Aphecetche, M.J. van Goethem, M. Hoefman, H. Huisman, J.G. Messchendorp and M. Volkerts.

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