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Abstract

The possibility of the observation of the Mott momentum in the distribution of the deuterons produced in the process $p + n \to d + \gamma$ in the first stage of the nuclear collision is presented. The correlation of the hard photon with the deuteron allows to select deuterons produced at the beginning of the collision.

Recent analysis of the hard photon production in heavy ion collisions shows the importance of the process $p + n \to d + \gamma$ in the description of the high energy part of the photon spectrum observed experimentally by the TAPS collaboration [1]. Also for the pion production, the inclusion of the process $p+n \to d+\pi$ seems to be necessary in order to describe the data. The two body phase-space and a weak dependence of the cross section $\sigma_{np\to d\gamma}$ on the energy makes it an important process in the high energy part of the photon spectrum. The deuteron in the final state is not Pauli-blocked, and if we allow for all deuteron momenta it would be the dominant process for high energy photons ($E_\gamma > 30$MeV). However, the process $p + n \to d + \gamma$ requires the existence of the bound state of the final deuteron. This means, that the deuteron momentum must be above the Mott momentum [2,3] if the influence of the surrounding nucleons is taken into account. In particular, deuterons with low momentum cannot exist at normal nuclear density. Typically, one finds $p_d/2 > p_{Mott}/2 \simeq 1.2p_F$ around the normal nuclear density [3].

This process was not previously discussed in the context of hard photon production in heavy ion collisions. Thus it seems important to test its relevance in a more specific way, using the $d - \gamma$ correlation. The correlation to a hard photon allows us to select the deuterons produced by this 2-body process. If we additionally impose a condition on the minimal energy of the photon or the maximal energy of deuteron, it selects the production at the early stage of the nuclear collision. Another way of producing deuterons involves 3-body collisions [3] and it also uses as a basic ingredient the value of the Mott momentum. Below, we show how in a more direct way the Mott effect can be tested in heavy ion collisions using the simpler $p + n \to d + \gamma$ process, where both the photon and the deuteron in the final state can be experimentally detected.

The $d - \gamma$ correlations will be studied in this work in a simple first chance collision model (FCCM) to understand the basic elements of this process. The assumption of the initial two Fermi spheres momentum distribution of the nucleons at this stage, defines the allowed deuteron momenta. The deuterons are emitted at 90° in the nucleus-nucleus center of mass (c.m.).

For describing the $p+n \rightarrow d+\gamma$ process in the FCCM we proceed as follows. We use the parameterization of the allowed region for the bound deuterons :

$$\int f(\frac{1}{2}\mathbf{p_d} - \mathbf{p}) | < \mathbf{p}|\phi > |^2 \frac{d^3p}{(2\pi)^3} < 0.2 \qquad , \tag{1}$$

where $< \mathbf{p}|\phi >$ is the deuteron wave function and $f(p)$ is the momentum distribution of the surrounding nucleons [3]. The application of this condition to the first stage of the collision, where the momentum distribution can be described by two Fermi spheres, defines the allowed deuteron momenta. The deuterons can be formed if : $p_d/2 \simeq p_F$, and the direction of p_d is transverse to the collision axis in the nucleus-nucleus center of mass. In other words, it means that the deuteron half momentum should find itself in between the Fermi spheres of the initial nuclei (see Fig. 1). This process is possible if the momentum of the center of mass of the two colliding nucleons is already large ($\simeq 2p_F$) and transverse. The minimal transverse momentum of the deuteron as a function of the energy of the collision is shown in Fig. 2. We see that around $E_{lab} = 140\mathrm{MeV/A}$ the lower limit on deuteron momentum disappears. Also at around 50MeV/A the kinematical restriction does not allow for the production of a $d-\gamma$ pair ($E_\gamma > 30\mathrm{MeV}$). In practice, the interesting energy range for the study of the dependence of the Mott momentum on the incident energy is $70 - 140\mathrm{MeV/A}$. It should be noted that the value of the minimal Mott momentum depends also relatively strongly on the chosen value for the Fermi momentum. In particular, if the reaction takes place at the nuclear surface, the Fermi momentum depending on the local density is low. Different curves in Fig. 2 which correspond to different values of p_F representing the effective Fermi momentum of an either lighter or heavier nuclei or the low density nuclear surface, are very different. The results presented below correspond to $p_F = 210\mathrm{MeV/c}$.

The probability of the production of the $d-\gamma$ pair per participant can be described in the first chance collision picture by [4]:

$$\frac{dP_{\gamma d}}{d^3p_\gamma\, d^3p_d} = \left(\frac{1}{2}\int\int \frac{d^3p_1}{(2\pi)^3}\frac{d^3p_2}{(2\pi)^3} f(\mathbf{p}_1)f(\mathbf{p}_2)\frac{|\mathbf{p}_1-\mathbf{p}_2|}{m}\frac{d\sigma_{np\to\gamma d}}{d\mathbf{p}_\gamma d\mathbf{p}_d}\Theta(\mathbf{p}_d,\mathbf{p}_{mott})\right) \times$$

$$\times \left(< \sigma_{nn} >_{eff}\, \frac{p_{coll}}{m}\rho_0^2\right)^{-1} \,, \tag{2}$$

where Θ is nonzero if the bound state deuteron of momentum $\mathbf{p}_d$ exists, and ρ_0 and $\sigma_{nn} = 40mb$ are the nuclear density and the average nucleon-nucleon cross section in medium. The first part of the right hand side in the above equation is the rate of the production of $d-\gamma$ pairs per unit volume and unit time. Dividing it by the second part of the right hand side, we obtain an estimate of the number of $d-\gamma$ pairs from the first stage of the collision per participant, where $< \sigma_{NN} >_{eff}$ is the effective Pauli blocked cross section [4] and p_{coll}/m is the relative velocity of the two nuclei. Notice, that since we deal with the non-isotropic momentum distribution at the beginning of the collision, the Mott momentum depends on the direction of the deuteron momentum, unlike in the nuclear matter. Thus the lowest Mott momentum is in the transverse direction (see Fig. 1), and in this direction deuterons will be emitted predominantly.

We have taken a parameterization of the cross section for the deuteron breakup process [1] :

$$\begin{aligned}\sigma_{\gamma d\to pn}[mb] &= \frac{32.3}{E_\gamma^{1.39}} \;,\quad E_\gamma < 50MeV \\ &= \frac{7.72}{E_\gamma^{1.01}} \;,\quad E_\gamma > 50MeV \;,\end{aligned} \tag{3}$$

where E_γ is in MeV, and extracted the cross section for the inverse process :

$$\sigma_{pn\to\gamma d}(\sqrt{s}) = \frac{3}{2}\frac{s-4m_n^2}{s}\sigma_{\gamma d\to pn} \;. \tag{4}$$

The isotropic distribution of the momentum of the produced deuteron and photon in the c.m. of the colliding $p-n$ pair is taken.

The resulting probability distribution as a function of the relative angle between the photon and the deuteron (now in the nucleus-nucleus c.m.) is shown in Fig. 3. We see that the $d-\gamma$ pair is not emitted back to back in this reference frame, and the distribution of the relative angles is broad, with a tail extending down to very small relative angles. This is, of course, due to the change of the reference frame, and the low number of back to back pairs is due to the condition $E_\gamma > 30$MeV in the nucleus-nucleus c.m.[1] . The spectrum of photons in the nucleon-nucleon c.m. frame is harder than the spectrum in the nucleus-nucleus c.m. frame. Thus we propose to impose energy cuts on the energy of the photon in the nucleon-nucleon c.m. and not on E_γ , except for the 'minimal' condition : $E_\gamma > 30$MeV.

The momentum distribution of the deuterons emitted in the reaction $p + n \rightarrow d + \gamma$ is shown with the solid line in the upper part of Fig. 4. According to our, expectations we find that the deuteron distribution is bounded from below by the value of the Mott momentum and from above by the kinematical restrictions. This shape of the deuteron momentum distribution is very different from the usual spectrum of light particles emitted in nuclear reactions. The deuterons emitted in the later stage of the collision, coming mostly from the 3-body process[2] , have momenta which can extend to lower values. Also the angular distribution would be very different for all deuterons and for deuterons emitted in the first stage of the collision. The deuterons produced in the 2-body process have momenta directed transversely in the nucleus-nucleus c.m. (Fig. 5). This reflects the existence of the gap between the two Fermi spheres which helps the formation of a bound deuteron (see Fig. 1). The 2-body process predicts a very narrow range of angles for the direction of the momentum

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[1]The Mott condition (1) implies that the deuterons are mostly emitted in the direction of c.m. momentum of the colliding pair, so that the momentum of the deuteron is increased when going from the nucleus-nucleus c.m. to the nucleon-nucleon c.m. reference of frame. The contrary is true for most of the photons.

[2]In the latter stage of the collisions, the momentum distribution is almost isotropic. The production of the deuteron from a 2-body process requires in that case the collision of two nucleons from the tail of the momentum distribution so that total momentum of the pair is larger than $p_{Mott} \simeq 2.4 p_f$.

of the deuterons observed in correlation with a hard photon, which in the laboratory frame of reference is around 40° in the forward direction for symmetric nuclei, i.e. for nuclei having the same effective Fermi momentum.

From the observed distribution of deuterons produced with a hard photon, we can deduce the Mott momentum corresponding to the initial phase space configuration in the collision. The very narrow angular distribution of the deuterons produced in the first stage of the collision can be used to reduce the background from the deuterons produced in 3-body collisions at latter stages of the reaction.

The possible background for the observation of the photon deuteron correlation involves mainly the bremsstrahlung photons and the deuterons produced in the 3-body process. These can form correlated like pairs either with a correlated γ or deuteron, either between themselves. The photon bremsstrahlung is known to give very low rates for high energy photons [1,6], comparable with the rate of the production from the $d - \gamma$ channel. This background can be further reduced if a supplementary condition on the photon energy is taken. As noted above, it is preferable to impose energy condition on the photon energy in the nucleon-nucleon c.m. Such a procedure does not reduce dramatically the cross section for the production of the the $d - \gamma$ pair (see the dashed curve in Fig. 4). On the other hand, the bremsstrahlung cross section decreases by several orders of magnitude when changing the energy of the photon from 30 MeV to 60MeV. Thus the background coming from the bremsstrahlung photons can be neglected in comparison to the background from the deuterons produced in 3-body collisions. The deuterons produced in 3-body collisions in the first stage of the reaction have the same angular distribution as the deuterons produced by the 2-body mechanism. Accordingly, they could, with a photon coming from the $d - \gamma$ channel[3] be mistaken as a correlated pair produced in the same nucleon-nucleon collision.

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[3]Since the bremsstrahlung photons give smaller yields for suitable conditions in energy, we do not take them into account

The probability of the production of a deuteron from the 3-body process, per 2-body collision participant, in the impulse approximation can be written as [5,3] :

$$\frac{dP}{d^3p_d} = \frac{3}{4}\int \frac{d^3p_1}{(2\pi)^3}\frac{d^3p_2}{(2\pi)^3}\frac{d^3p_3}{(2\pi)^3} d\Omega f(\mathbf{p}_1)f(\mathbf{p}_2)f(\mathbf{p}_3)(1-f(\mathbf{p}_1^{'}))\frac{|\mathbf{p}_1-\mathbf{p}_2|}{m}$$
$$\frac{d\sigma_{NN}}{d\Omega}| < \mathbf{p}_2^{'} - \mathbf{p}_3|\phi > |^2\Theta(\mathbf{p}_2^{'}+\mathbf{p}_3, \mathbf{p}_{Mott})\left(<\sigma_{NN}>_{eff}\frac{p_{coll}}{m}\rho_0^2\right)^{-1} . \quad (5)$$

In the bottom part of Fig. 4, we show results for the probability distribution of deuterons produced in the 3-body process per 2-body collision. We see that the yields are higher than for the 2-body process, but are of the order of 10^{-7} . The probability for a statistical correlation is proportional to the product of the probabilities , thus very small, but also to the square of the number of participants unlike the probability for true correlations which is proportional to the number of participants. Also deuterons produced at later stages of the collision would, at some rate, populate the same angular region as the deuterons produced in the first collisions, increasing the deuteron background. However, we expect that the 2-body process : $p+n \rightarrow d+\gamma$, can be extracted by the simultaneous hard photon and deuteron observation, since it leads to a very special momentum distribution of deuterons, which could be observed even if some non-negligible background is present. The deuteron distribution obtained in this manner would learn us about the Mott mechanism in nuclear matter. The photon spectrum obtained in correlation with a deuteron can be compared to the total photon yield in order to show directly which part of the spectrum is due to the photons produced in the $d-\gamma$ channel. This channel of hard photon production is important especially at energies above 140MeV [1] . Finally, it should be noted that the absorption of the deuterons is quite substantial unlike for the photon. It can be estimated, taking $\sigma_{dN}^{ine} \simeq 2\sigma_{NN}$, that only about 20% of the produced deuterons survive in the collision of medium size nuclei. Similar absorption rates are estimated in microscopic calculation [3]. However, the same is true also for the background deuterons, so the observation of the Mott effect in nuclear matter could be possible. We estimate that after absorption of deuterons, the probability of the production of $d-\gamma$ pair is 10^{-6} per participant in the collision of medium size nuclei with energy 90MeV/A. It should be noted that the deuteron nucleon cross section in medium is largely unknown. In particular, it is expected that the cross section for a weakly bound deuteron with momentum close to the Mott momentum can be very large [7]. Another important effect may be due to the elastic scattering of the produced deuterons. Thus, we expect a broadening of the observed angular distributions of deuterons and of the angular spectrum of the $d-\gamma$ pairs. Another mechanism of deuteron absorption could be the deuteron dissociation. This can occur if the deuteron, enters a higher density region while traveling in the nuclear medium. If in such a higher density region the deuteron is not bounded, it would dissociate. Similar process can occur if the gap between the two Fermi spheres (Fig. 1) becomes filled in the course of the collision before the deuteron escapes the nuclear medium. However, the dissociation mechanism is less important than the deuteron breakup by the nucleon-deuteron collisions.

In summary, we have proposed the observation of the correlation of a hard photon with a deuteron produced in heavy ions collision. In the range of incident energies : $70 < E_{lab} < 140 MeV/\mathrm{A}$, the available phase space for the bound deuterons is strongly reduced by the Mott effect. This can serve as a way of the experimental observation of the Mott momentum for deuterons. The experimentally estimated value of the Mott momentum could be used as a phenomenological parameter in the calculations of heavy ion collisions involving the formation of a deuteron in the final state. It would be also interesting to compare the observed conditions of the in medium deuteron formation to the theoretical calculations of the nuclear medium influence on the deuteron formation. The observation of the $d-\gamma$ correlated pairs will also represent a direct measurement of the photon yield produced in the reaction $p + n \rightarrow d + \gamma$, which is believed to be an important component of the total hard photon yield in intermediate energy nuclear collisions. The observation of the $d-\gamma$ correlation represents the first possibility to estimate the percentage of the hard photon yield from a definite channel. The production of deuterons at the first stage of the collision is determined by the allowed momenta for the deuterons (Fig. 1). Thus the experimental observation would give us information on the mechanism of the deuteron formation in the nuclear medium.

The main subject of this work was the implication of the Mott condition for the creation of a bounded deuteron in nuclear medium on the observed spectra of deuteron. However, it should be noticed that the reaction discussed in this work : $p + n \to d + \gamma$, seems to be important also for the description of the hard photon spectra. This channel of the photon production has not been up to now addressed in the microscopic calculations of heavy ion collisions.

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Figure captions

Fig.1

The distribution of initial longitudinal and transverse momenta of colliding nucleons (the two intersecting Fermi spheres) for $p_F = 210$MeV and a collision energy of 90MeV/A. The dots inside the spheres represent the momenta of the nucleons that have produced the deuteron in the 2-body process. A strong reduction of the cross section in comparison to the free case is expected due to the restriction on the initial phase space. The half of the deuteron momentum must be located outside the outer line (representing half of the angle dependent Mott momentum). The points in the outside region represent half of the momenta of deuterons produced in correlation with a photon ($E_\gamma > 30$MeV) .

Fig.2

The lowest value of the Mott momentum, i.e. in the transverse direction, as a function of the collision energy. The dashed, solid and dotted lines are calculated for the Fermi momentum $p_F = 180$, 210 and 250MeV/c respectively.

Fig.3

The probability of the production of a deuteron-photon pair per nucleon collision as a function of the relative angle $\Theta_{\gamma d}$ at the collision energy of 90MeV/A ($E_\gamma > 30$MeV).

Fig.4

The upper part of the figure :

(i) the solid line denotes the probability distribution for deuterons originating from the 2-body process at 90° in the c.m. of the nucleon-nucleon collision, as a function of the deuteron momentum for the same conditions as in Fig. 3.

(ii) the dashed line denotes the probability distribution for deuterons originating from the 2-body process at 90° in the c.m. of the nucleon-nucleon collision, but with the supplementary condition that the energy of the photon in the reconstructed c.m. of the nucleon-nucleon collision is larger than 60MeV. In the bottom of the figure the probability distribution of the deuterons from the 3-body process at 90° in the c.m. of the nucleon-nucleon collision is shown as a function of the deuteron momentum at the energy $90 MeV/\mathrm{A}$.

Fig.5

The probability distribution of the emitted deuterons as a function of the angle in nucleus-nucleus c.m. for the same conditions as in Fig. 3.

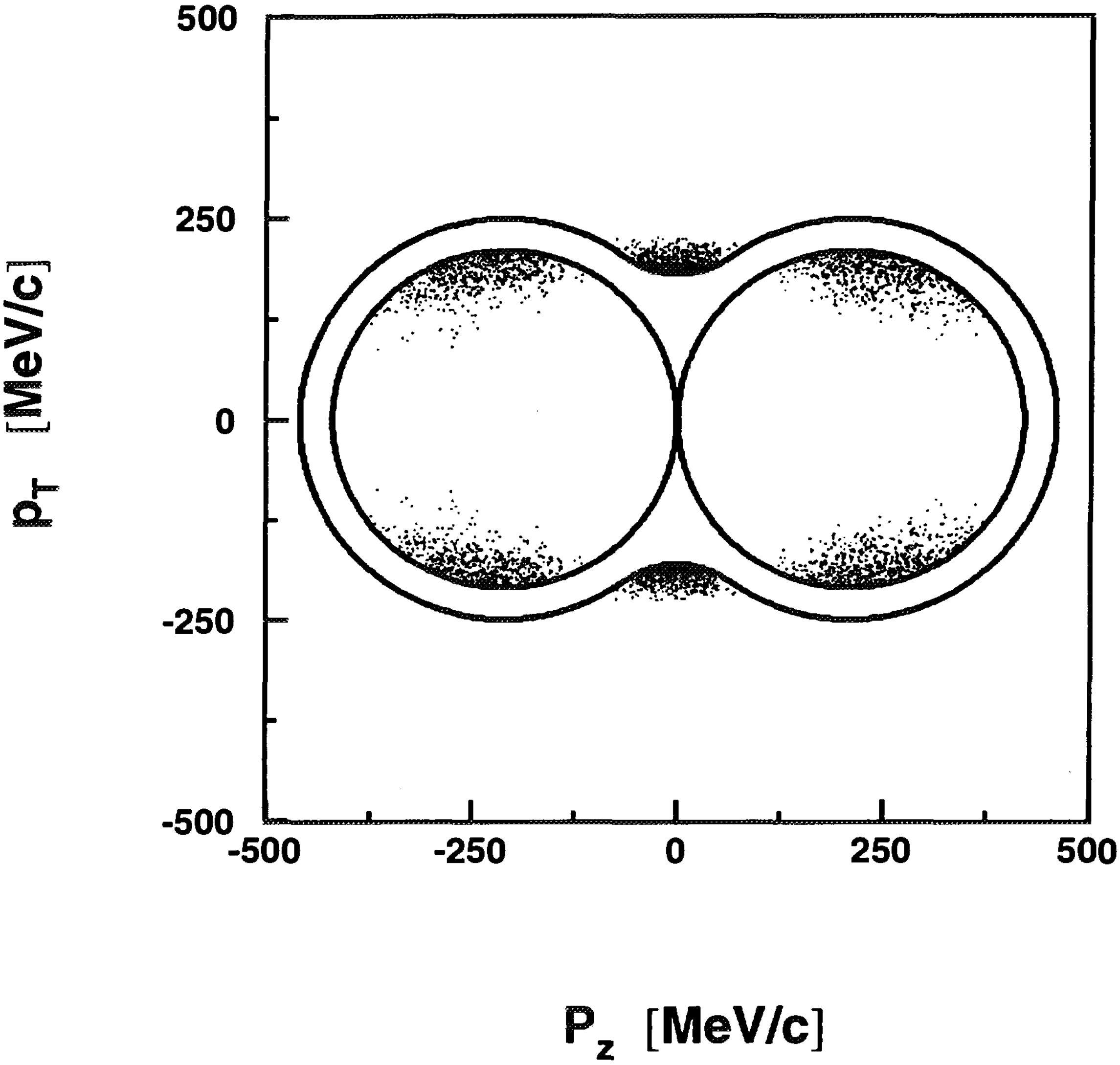


Fig. 1

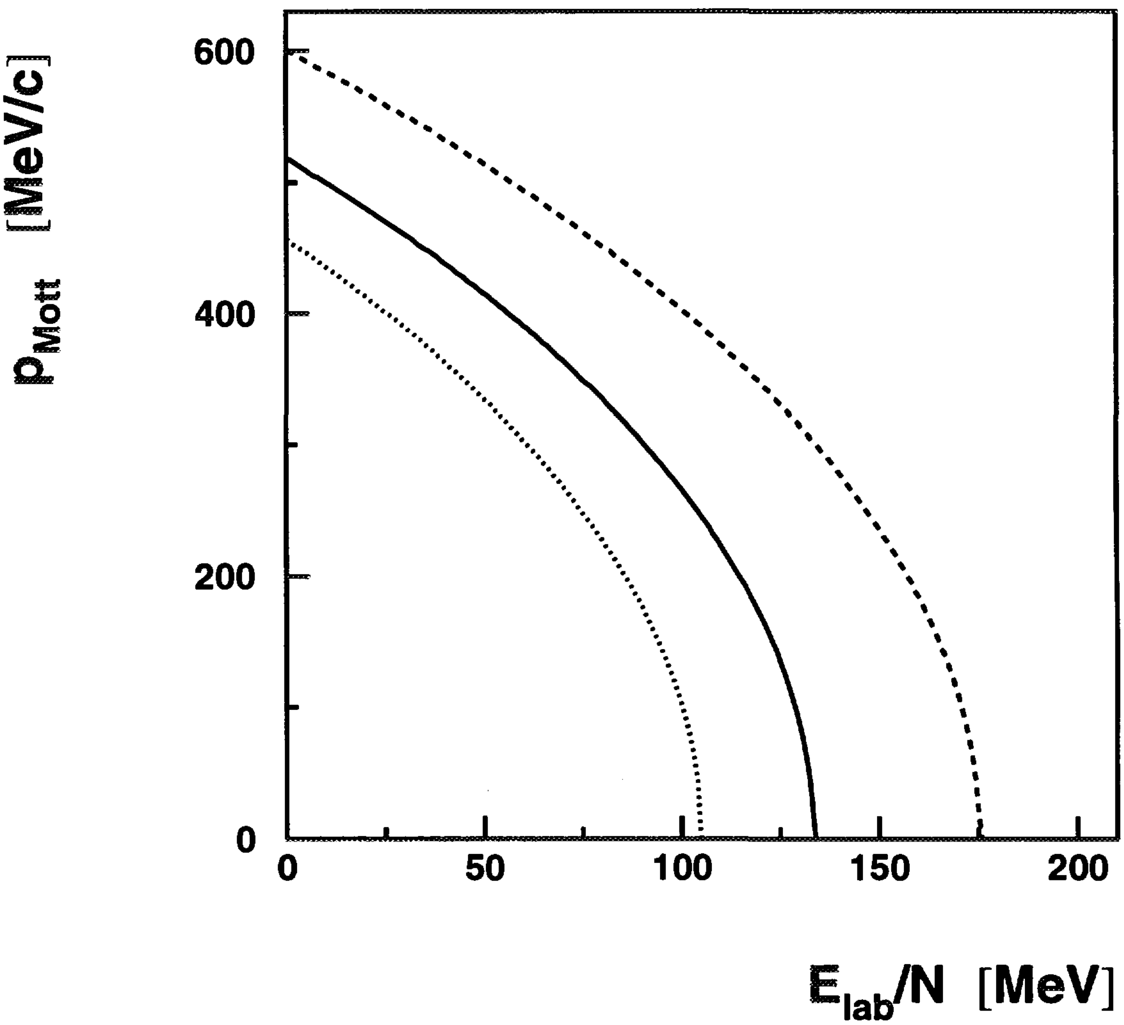
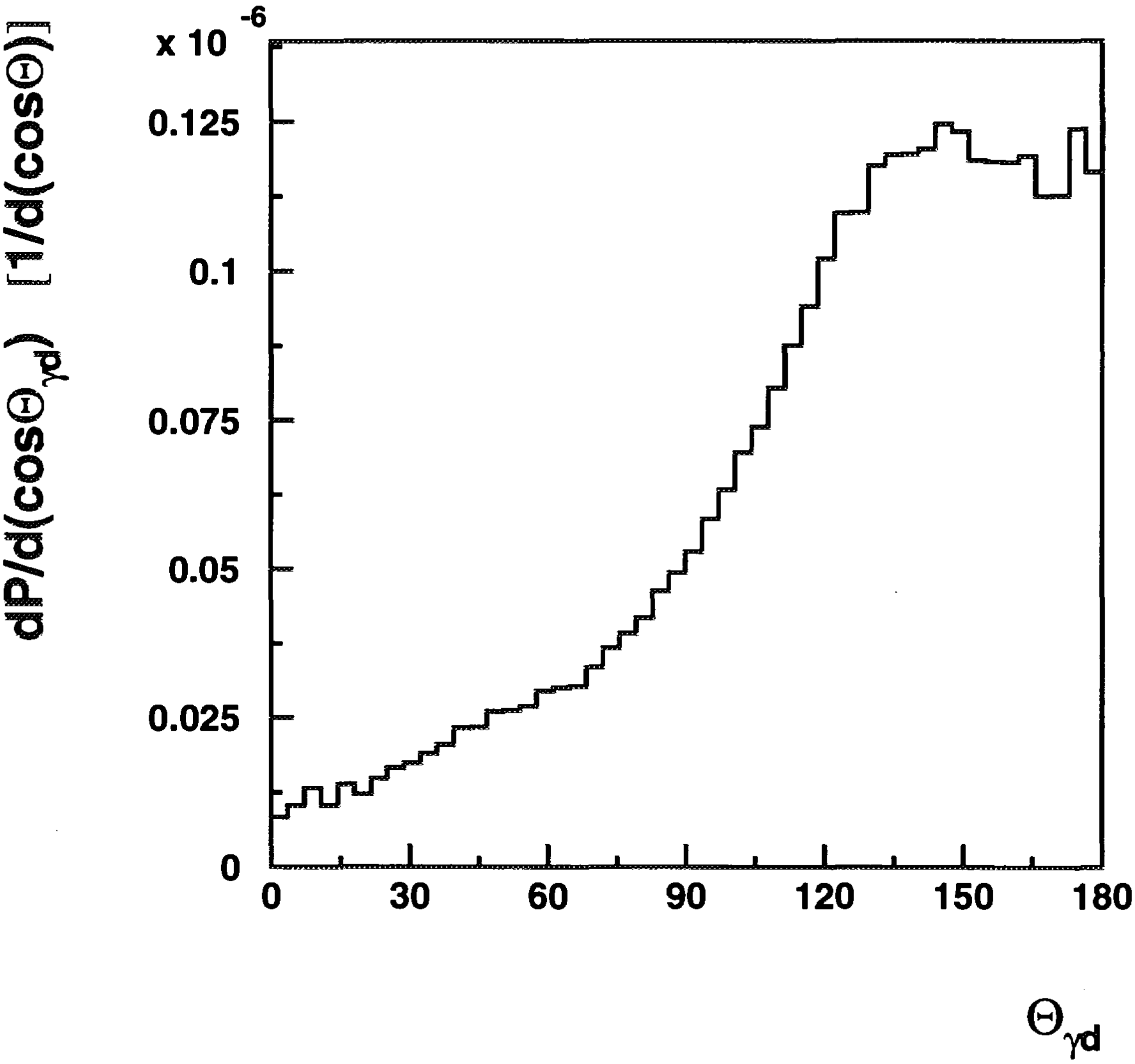


Fig. 2


dP/d(cosΘ_γd) [1/d(cosΘ)]
x 10^-6
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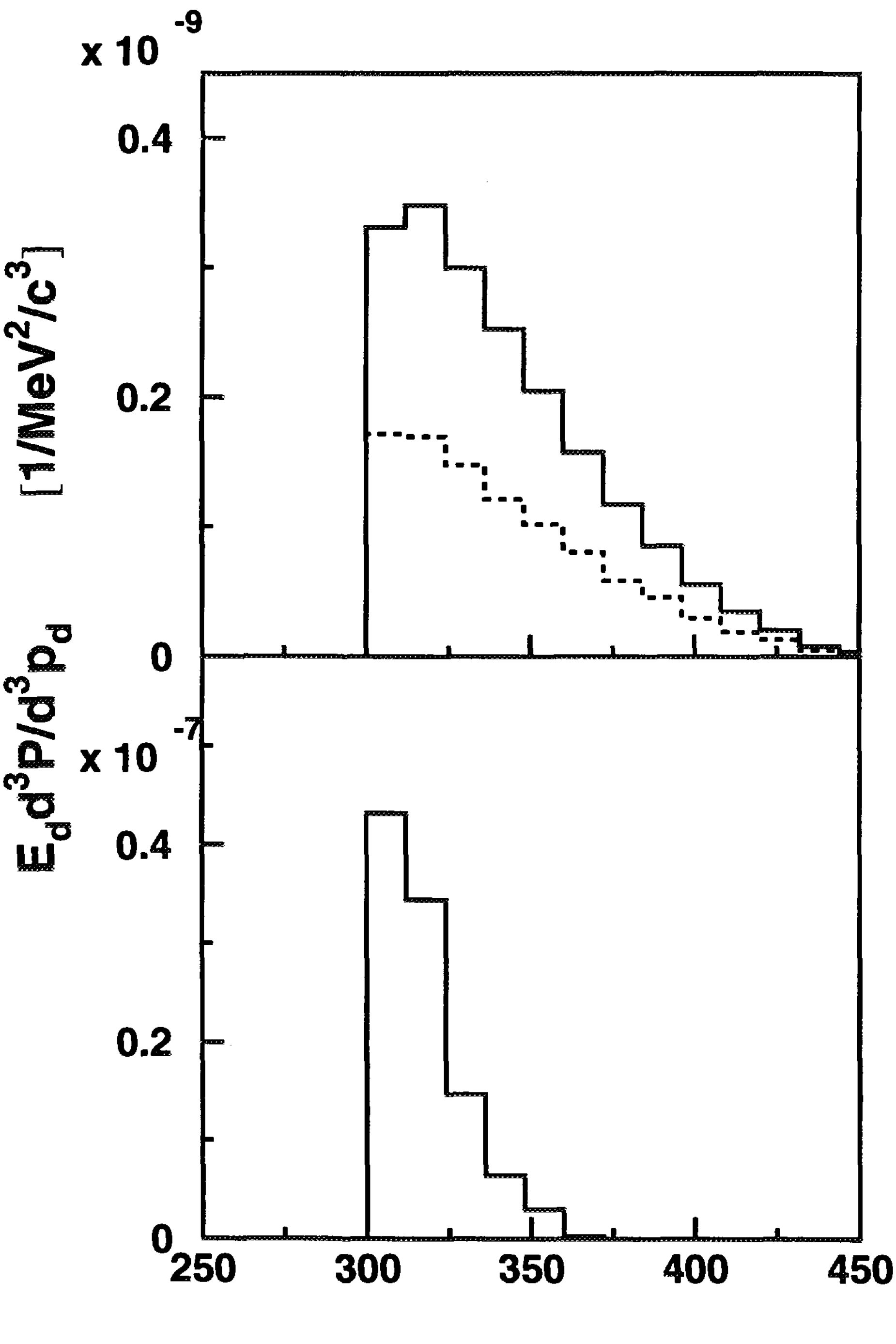
0.075
0.05
0.025
0
0
30
60
90
120
150
180
Θ_γd

Fig. 3



x 10 -9
0.4
0.2
0
x 10 -7
0.4
0.2
0
250
300
350
400
450
$E_d d^3P/d^3p_d$ [1/MeV²/c³]
P_d [MeV/c]

Fig.4

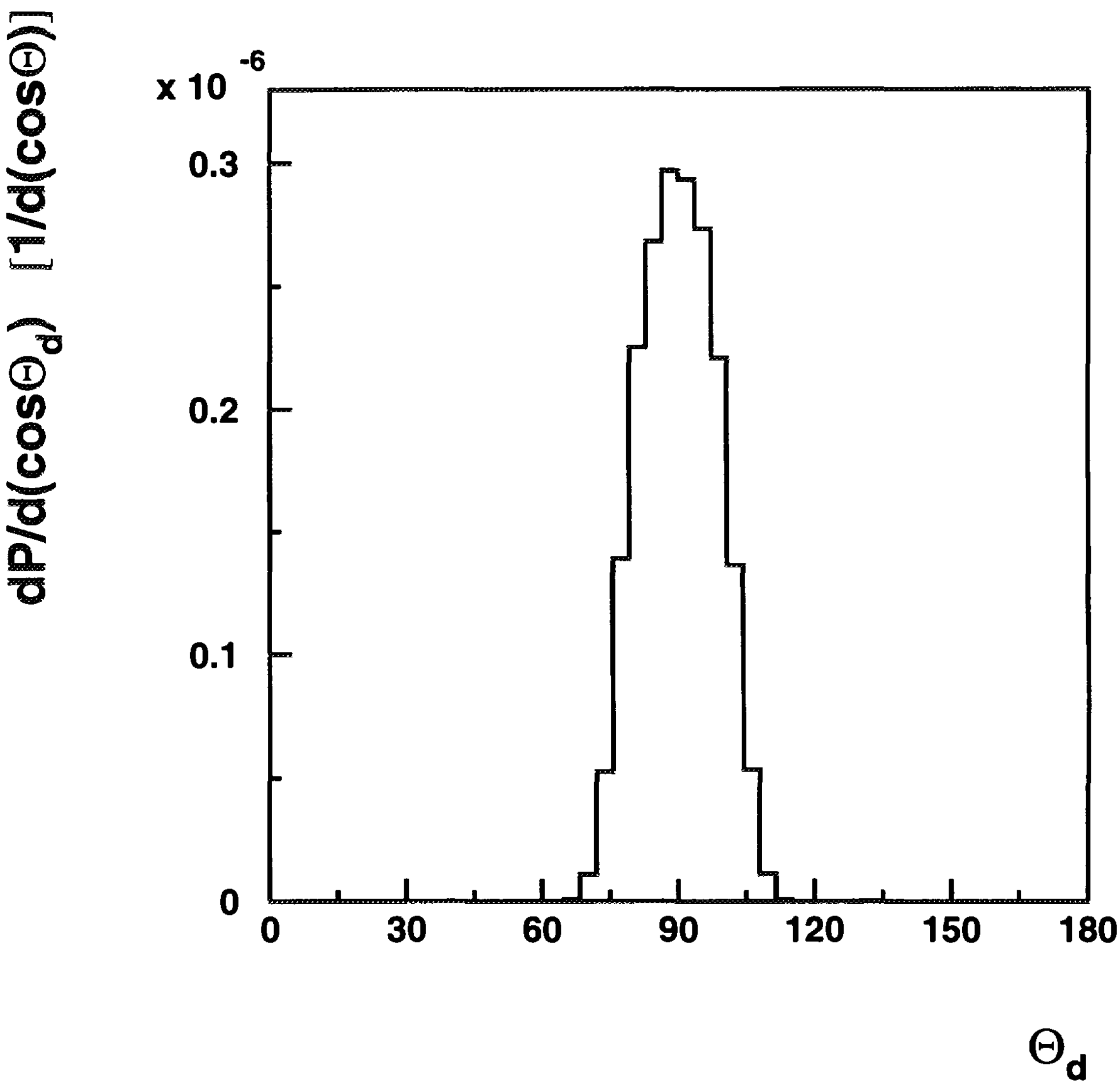


Fig. 5