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V.I.Komarov, S.Tesch

CALCULATION OF ABSORPTION FACTORS IN NUCLEAR REACTIONS WITH MEDIUM-ENERGY PROTONS

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Abstract

Nuclear transparencies for reactions at intermediate energies in straight-line approximation are estimated. Some peculiarities as nuclear matter distributions and total cross sections for several nuclear processes are discussed.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

1. Introduction

During passage of projectiles and secondary nuclear reaction products through nuclear matter absorption losses arise as the result of the interaction of these particles with the nucleons of the nucleus. If one intend to compare the experimental data with other processes or theoretical predictions, the absorption effects must be considered. These absorption losses in dependence on the nuclear processes under study and the chosen nuclear matter distributions can be of considerabl amount.

The calculation method described in this paper has been used to estimate absorption factors for nuclear reaction cross sections of medium-energy protons on light nuclei. In processes of quasielastic scattering on clusters (p, NX) and fragmentation processes with pion production $(p, \pi X)$, where $X = {}^{2,3}H$, ${}^{3,4}He$, absorption factors were needed to compare the data with shell model predictions of effective cluster numbers /1/. Studying the energy dependence of quasielastic deuteron knock-out we had to consider the absorption effects to get information on the reaction mechanism in comparison to elastic pd backward scattering /2/. Recently it was shown experimentally that a considerable part of the inclusive proton spectrum in backward direction is correlated with energetic protons in forward direction /3/. To estimate the amount of this part we had also to calculate the corresponding absorption effect on the forward-emitted proton.

Before us Kalinkin and Shmonin /4/ estimated absorption losses to understand the experimental yield of deuterons in the kinematical regions of quasielastic scattering and pion production. As the method described in ref. /4/ is of standart type, it can be applied also to other processes. For instance, the same method was used to extract information on the quark structure of hadrons by calculating the quark absorption probability in nuclear matter /5/. Also in electron scattering processes, e.g. of type (e, e' d) it was shown that wave distortions of the outgoing particles must be included to extract information on effective cluster numbers and short-range correlations in nuclei (see, e.g., /6,7/). For the process ^6Li (e, e' p) we compared our estimations of the nuclear transparency with optical model calculations (see, ref. /6/). With the corresponding proton-nucleon cross sections for energies of 100 MeV and higher we found complete agreement with the mean value of 1p and 1s proton absorption.

2. Description of the calculation method

General remarks. The calculation method is based on the fact that at some hundreds of MeV for the primary protons as well as for the emitted particles (condition of large momentum transfer) the straight-line approximation can be used. The procedure described in this paper is completely analogeous to the one applied in ref. /4/. This method needs only simple conceptions of the target nucleus -- geometrical characteristics and density distributions of nuclear matter. A problem of course is the density distribution suitable for clusters in nuclei, which are in general unknown. In the calculations it turned out the absorption values to depend rather sensitive on these density distributions. Beyond it into the absorption estimations enter the total cross sections for the interaction of primary and emitted particles with the nucleons.

Calculation method. For the nuclear process $p + A \rightarrow X + \ldots$ (Knock-out of particle X by protons p from a nucleus with mass number A) the absorption factor is given by the following relation

$$\gamma = \frac{\int\limits_{-\infty}^{+\infty} d^2 b \, dz \, \rho_X(b,z) \, \Gamma_p(b,z) \, \Gamma_X(b,z)}{\int\limits_{-\infty}^{+\infty} d^2 b \, dz \, \rho_X(b,z)} , \qquad (1)$$

if the absorption of the projectile and outgoing particle is taken into account. Using the multiple scattering theory one gets for the particles p and X the expressions

$$\Gamma_p(b,z) = \exp\left(-\sigma_{pN} T_-(b,z)\right) \qquad (2a)$$

$$\Gamma_X(b,z) = \exp\left(-\sigma_{XN} T_+(b,z)\right) \qquad (2b)$$

where the profile functions $T_-(b,z)$) and $T_+(b,z)$) are expressed in terms of the nuclear density $\rho(b,z)$

$$T_-(b,z) = A \int\limits_{-\infty}^{z} dz \, \rho(b,z) \qquad (3a)$$

$$T_+(b,z) = A \int\limits_{z}^{+\infty} dz \, \rho(b,z) \qquad (3b)$$

Relation (2a) gives the probability that the projectile p reaches the point z with impact parameter b without any interaction, while expression (2b) is the probability for particle X leaving the nucleus from point (b, z) without interaction.

<u>Density distributions</u>. For nuclear matter distributions according to relations (3a), (3b) one can use well known formula with parameters taken from eA scattering experiments (see, e.g., /8/). For light nuclei it is customary to use

$$\rho(b,z) = C\left(1+\eta\,\frac{b^2+z^2}{a_0^2}\right)\exp\left(-\frac{b^2+z^2}{a_0^2}\right) \qquad (4)$$

with $\eta = \frac{Z-2}{3}$, Z being the charge number of the target nucleus. To get the correct normalization

$$4\pi\int_0^\infty \rho(r)\,r^2\,dr = 1 , \qquad (5)$$

the normalization constant C is $C = \frac{2}{Z a_0^3 \pi^{3/2}}$.

For very light nuclei we used also formula (4) or a pure Gaussian distribution with the parameter a_0 calculated under the condition the mean square radii of these distributions to be the same as for the exact distribution. The estimations due to expression (1) with these approximated distributions agreed within an accuracy of about 5%.

On the other hand, in dependence on the reaction process under study the corresponding density distributions $\rho_x(b,z)$ in relation (1) must be chosen suitably. For instance, in the independent - particle model, the probability of finding n nucleons inside the volume element near point r is proportional to $\rho^n(r)$, that is decreases rapidly near to the nuclear surface. Therefore, effective cluster numbers extracted from experiment can be essentially overestimated, if one uses values from calculations with $\rho_x = \rho^n(r)$ (see, e.g. /4/). To choose the nearly correct density distributions one can utilize the commonly accepted assumption that they are of more or less peripheral character. An idea of the dependence of γ estimations on different nuclear matter distributions $\rho_X(r)$ may give ref. /1/ and the tables in the appendix, where we used $\rho_X = \rho(b,z)$ of type (4) and $\rho_X = \rho^n(b,z)$ with n = 2 and 1/2 . To get the correct normalization (5),

$$C = \frac{4\sqrt{2}}{a_0^3\,\pi^{3/2}\left(Z + \frac{15}{72}\left(Z^2 - 4Z + 4\right)\right)}$$

for the n = 2 case is found. For n = 1/2 integral (5) must be solved numerically. As an example, one gets C = 0.006755 fm^{-3} for ^{12}C with a_0 = 1.64 fm.

<u>Cross sections.</u> To calculate the absorption factor γ the corresponding cross sections for the projectile and final particles are needed (see expression (2a), (2b)). For the total cross section of the primary proton one uses /9/

$$\sigma_{pN} = \frac{1}{2}\left(\sigma_{pp}^{tot} + \sigma_{pn}^{tot}\right) .$$

The cross section σ_{XN} must be taken in accordance with the particle X measured, the experimental set-up, angular acceptance of detectors, etc. For the analysis of deuteron knock-out we used /10/

$$\sigma_{dN} = \sigma_{pp} + \sigma_{pn} - \frac{(1-\rho_p\rho_n)\,\sigma_{pp}\sigma_{pn}}{4\pi(D + A_p + A_n)}$$

with the corresponding parameters ρ , A , D for medium-energy nucleons. It should be noted that the screening term of the deuteron total cross section takes only a small effect on the absorption. We found an enlargement of γ of about 5% without this correction term.

For heavier fragments X in part one can find experimental data /11/. Experimentally unknown cross sections must be calculated with the help of the nucleon-nucleon cross sections σ_{NN} at the corresponding reduced kinetic energies. Comparisons with experimental data show that for fragments ^3H, ^3He and ^4He these cross section values must be reduced by about 15% and 20%, respectively.

For the knock-out of heavy particles from light nuclei it should be taken into account that in this case the mass number of the final nucleus is considerably reduced leading to a corresponding reduction of the absorption effect. Therefore, the value A in relation (3b) should be replaced by $A - N_X$, N_X being the mass number of the particle X . As an example we note this procedure leading to a γ reduction of about 10% for the ^4He Knock-out from Carbon at 1 GeV.

In relation (1) instead of $\Gamma_X(b, z)$ a product of several probabilities can appear, if one considers more than one particle in the final state, for instance, in processes with two or three outgoing protons as studied in /3,12/.

Numerical method. If one uses in the case of light nuclei density distributions of type (4), than the integrals of relation (1) essentially can be solved with Hermite-Tshebyshev polynomials /13/. This method in the computer code presented in this work has been employed. For the denominator of expression (1) one gets in this manner

$$\int_{-\infty}^{+\infty} d^2b\, dz\, \varrho(b, z) = \sum_{n=1}^{N} \sum_{k=1}^{K} f(b_n, z_k)\, b_n A_n A_k .$$

The values A_n , A_k for the crossing points b_n , z_k are tabulated /13/. A remainder of the numerator is integrated by using the Simpson formula. It has been proved for the γ estimation within an accuracy of 3% to be sufficient to use N = 5 and K = 8. For Fermi-type nuclear matter distributions of heavy nuclei γ is calculated by using standart methods of two-fold integration.

Appendix

As an example the absorption factor γ for the process $p + {}^{12}C \longrightarrow 2p + \ldots$ at 640 MeV is estimated. In expression (1) the density distribution $\varrho_x(b, z)$ of form (4) is used. The cross sections for the forward and backward emitted protons are chosen in accordance with the experimental conditions of ref. /3/. With all three cross sections $\sigma = 0$ one gets of course $\gamma = 1$. The common factor of the integrals due to relation (1) is omitted. This factor is $2\pi\, a_o^3\, c$, yielding the denominator value 1 within the accuracy of the numerical calculation of the integral.

In table 1 the absorption factors $\gamma(\varrho^n)$ with $n = 1/2, 1, 2$ for process $p + {}^{12}C \longrightarrow 2p + \ldots$ are listed. Table 2 contains absorption coefficients $\gamma(\sqrt{\varrho})$ and $\gamma(\varrho)$ for several knock-out reactions, at which only the absorption effect due to the heavy fragment is taken into account.

Kauff
Tauh

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Table 1

Absorption factors for process $p_o + {}^{12}C \rightarrow p_1 + p_2 + \ldots$ with cross sections σ_0, σ_1, σ_2 for primary and outgoing protons according to the experimental conditions

σ_0 (mb)	σ_1 (mb)	σ_2 (mb)	Absorption factors $\gamma(\sqrt{\varrho})$	$\gamma(\varrho)$	$\gamma(\varrho^2)$
38	-	-	0.61	0.51	0.44
38	20	-	0.47	0.33	0.23
38	20	15	0.42	0.27	0.18
38	-	15	0.54	0.42	0.35
-	20	-	0.74	0.66	0.61

Table 2

Absorption factors for several knock-out processes with protons on ^{12}C

Process	Momentum (GeV/c)	Absorption factor $\gamma(\sqrt{\rho})$	$\gamma(\rho)$
(p, Nd)	1.6	0.37	0.22
(p,N^{3}He)	1.8	0.34	0.20
(p,π ^{3}He)	1.5	0.31	0.17
(p, N^{4}He)	1.9	0.29	0.15
(p,π ^{4}He)	1.6	0.25	0.11

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РЕДАКТОР ТЕКСТОВ
(1.01.78)

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      *RO
      *W:
            PROGRAM LIN3P
      C-----INTERACTION OF PROTONS WITH CARBON-12
      C ----EXAMPLE: INCIDENCE ENERGY 64 MEV
      C-----CROSS SECTIONS TAKEN IN ACCORDANCE WITH TH
                            E EXPERIMENTAL CONDITION
      C-----ONE PROTON WITH ENERGY 28 MEV IN FORWARD
                            DIRECTION
      C-----ONE PROTON WITH ENERGY 10 MEV IN BACKWARD
                            DIRECTION
      C-----PRIMARY AND FINAL PROTONS IN THE ABSORPTIO
                            N CALCULATION INCLUDED
            DIMENSION FU1(5,8),    FU2(5),    FU3(5,8)
            COMMON/NULL/B(5),Z(8)
            COMMON/POL)/AB(5),AZ(8)
            COMMON/VAR CONST,A,C,A ,SP1,SP2,SPB
            CONSQ= .02 672688
            CONSW= .0 754851
            READ   8    ,    (B(I) I=1,5)
          8 FORMAT(5F   8)
            READ 5 , (Z(I) I= ,8)
          5 FORMAT(8F   7)
            READ  5 ,    (AB(I),I= ,5)
         51 FORMAT(5F   .9)
            READ 5 ,    (AZ(I),I=1,8)
         5  FORMAT(8F1  .9)
            PRINT2
            PRINT2
        2   FORMAT(//3 X,12HCOEFFICIENTS//)
        2 1 FORMAT( 6X 'I'  5X,'B(I)',1 X,'AB(I)'///)
            DO 25  I=  5
         25 PRINT6,I,B(I),AB(I)
            PRINT2 2
        2 2 FORMAT(/// 6X,'I', 5X,'Z(I)',1  X,'AZ(I)'//
                            /)
            DO  7   I= ,8
          7 PRINT6,I,Z(I),AZ(I)
          6 FORMAT( H  5X I1,5X 2E15.9)
            READ 1,  A   C   A
          1 FORMAT(3F   5)
            CONST=2./( *A **3*SQRT(3.141592**3))
                AD=FSQ(  .)
            PRINT2 5
        2 5 FORMAT(/ / X,'MASS NUMBER',1 X,'CHARGE',1
                            X,'RADIUS',1 X,
           *'INTEGRAL WITHOUT ABSORPTION')
            PRINT   3   ,A C,A  AD
            PRINT  99
            DO  1      I=  5
            RHO=CONST*( .+(C-2.)*B(I)**2/3.)
           **EXP(-B(I)**2)
            RAD=B(I)*A
            RHOL=RAD**2*CONST*(1.+(C-2.)*B(I)**2/3.)*E
                            XP(-B(I)**2)
            RHOQ=RAD**2*CONSQ*((1.+(C-2.)*B(I)**2/3.)*
                            *2)*EXP(-2.*B(I)**2)
            RHOW=RAD**2*CONSW*SQRT( .+(C-2.)*B(I)**2/3
                            .)*EXP(-.5*B(I)**2)
            PRINT   1    ,B(I),RAD,RHO,RHOL,RHOQ,RHOW
        1   CONTINUE
         99 FORMAT(/14X,4HB(I),7X,6HRADIUS,3X,3HRHO,3X
                            ,35HDENSITY DISTRIBUTION
```

```
   SS WITH RHO=LINEAR/SQUARE/SQUARERUOT/)
101 FORMAT(10X,2F10.3,4E10.3/)
  3 FORMAT(/10X,3F20.2,F20.6)
208 FORMAT(//20X,'INCIDENCE ENERGY=',F6.2,5HME
                         V,10X,'TOTAL CROSS SECTI
   *ON=',F6.2,2HMB)
  2 FORMAT(2F10.5)
206 FORMAT(//10X,'ENERGIES AND CROSS SECTIONS
                         FOR FORWARD AND BACKWARD
   * PROTONS'/)
301 FORMAT(10X,19HFORWARD PROTON WITH,5X,F6.2,
                         3HMEV,5X,F8.3,2HMB,20X,
   *20HBACKWARD PROTON WITH,5X,F6.2,3HMEV,5X,F
                         8.3,2HMB)
    READ  2  ,  ENUL,SP1
    READ  2  ,ENB,SPB
    PRINT   208    ,ENUL,SP1
    READ  2  ,  EN2,SP2
    PRINT206
    PRINT  301   ,EN2,SP2,ENB,SPB
    SP1=SP1/10.
    SP2=SP2/10.
    SPB=SPB/10.
    CALL  SIMP(FU3)
    CALL  FU12(FU1,FU2)
    GAM=0.
    DO  10  I=1,5
    DO  10   J=1,8
 10 GAM=GAM+FU1(I,J)*FU2(I)*FU3(I,J)*AB(I)/FSQ
                         (0.)
    PRINT  15  ,  GAM
 15 FORMAT(//20X,'ABSORPTION GAMMA=',F10.6)
    PRINT300
300 FORMAT(//30X,'ABSORPTION IN DEPENDENCE ON
                         IMPACT PARAMETER'/)
    PRINT   302
302 FORMAT(/32X,4HB(I),15X,6HRADIUS,15X,9HDGAM
                         MA/DB/)
    DO 61    I=1,5
    RAD=B(I)*A0
    BEAB=0.
    DO 60     J=1,8
 60 BEAB=BEAB+FU1(I,J)/B(I)*FU2(I)*FU3(I,J)*EX
                         P(-B(I)**2    )/AD
 61 PRINT   62  ,B(I),RAD,BEAB
 62 FORMAT(1H0,20X,3F20.10)
    END
    SUBROUTINE  SIMP(FU3)
    DIMENSION  S(5,8),    FU3(5,8)
    COMMON/NULL/B(5),Z(8)
    COMMON/VAR/CONST,A,C,A0,SP1,SP2,SPB
    G=2.
    H=0.2
    JMAX=30
    DO  100  I=1,5
    DO   10   J=1,8
    S(I,J)=(1.+(C    =2.)*(B(I)**2+Z(J)**2)/3.
                         )*EXP(-Z(J)**2    )
    DO 11    JJ=1,JMAX
    ZZ=Z(J)+H*JJ
    G=6.-G
 11 S(I,J)=S(I,J)+(1.+(C     -2.)*(B(I)**2+ZZ**
                         2)/3.)*EXP(-ZZ**2    )*G
    S(I,J)=S(I,J)*H/3.
 10 FU3(I,J)=EXP(-    (SP2-SPB-SP1)*CONST*A0*A*
```

```
                                    S(I,J)
                 * *EXF(-B(I)**2))
             1 0 CONTINUE
                 RETURN
                 END
                 SUBROUTINE  FU12(FU1,FU2)
                 DIMENSION  FU1(5,8),   FU2(5)
                 COMMON/NULL/B(5),Z(8)
                 COMMON/POLY/AB(5),AZ(8)
                 COMMON/VAR/CONST,A,C,AV,SP1,SP2,SPB
                 DO  1  I=1,5
                 F2= .
                 DO 2  J=1,8
                 F1=        +(C    -2.)*(B(I)**2*Z(J)**2)/3
                 FU1(I,J)=F    *AZ(J)  *B(I)
               2 F2=F2+(1.+(C    -2.)*(B(I)**2/3.*Z(J)**2/3
                                 .))*AZ(J)*EXP(-B(I)**2)
               1 FU2(I)=EXP(-CONST*AV*A*F2*    (SP1+SPB))
                 RETURN
                 END
                 FUNCTION FSQ(ALPHA)
                 COMMON/NULL/B(5),Z(8)
                 COMMON/POLY/AB(5),AZ(8)
                 COMMON/VAR/CONST,A,C,AV,SP1,SP2,SPB
                 FSQ=ALPHA
                 DO     I=1,5
                 DO  1    J=1,8
               1 FSQ=FSQ+B(I)*(1.+(C    -2.)*(B(I)**2*Z(J)*
                                 *2)/3.)    *AB(I)*AZ(J)
                 END
               ФАЙЛ 1        :ЗАПИСАНО   133 КАРТ (  ТР.)
          *EE
*END FILE
```