# MONTE CARLO INTRANUCLEAR CASCADE CALCULATIONS ON $C^{12}$ WITH MEDIUM-ENERGY PHOTONS

E. Gradsztajn
Institut du Radium, Laboratoire Joliot-Curie, Orsay, Seine-et-Oise, France
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It is generally considered that the Monte Carlo cascade calculations cease to be valid when the mass number of the target nucleus is too low. However, it has been shown by Abate et al.[1] and Bertini[2] that results compatible with experiments may be obtained down to $A = 12$. The present calculations were performed as an attempt to extend further the comparison with experimental results including, as Abate et al. did, the assumption of $\alpha$ clusters in light nuclei. The presence of $\alpha$ clusters is taken into account through the probability $P$ for protons to collide with such clusters. A comparison is made between results obtained with $P = 40\%$, $P = 30\%$, and $P = 0\%$.

Our program is essentially the one used formerly[3] with the following values for the nucleon-nucleon scattering cross sections[4]:

$$\sigma_{nn} = \sigma_{pp} = (10.63/\beta^2 - 29.92/\beta + 42.9) \text{ mb},$$

$$\sigma_{np} = \sigma_{pn} = (34.10/\beta^2 - 82.2/\beta + 82.2) \text{ mb};$$

and the differential cross section[4]:

$$d\sigma/d\Omega = K(A\cos^4\theta + B\cos^3\theta + 1),$$

where $A$ and $B$ vary with incident nucleon energy.

For $(p, \alpha)$ collisions we used experimental values of $d\sigma/d\Omega$ given by Selove and Teem[5] and Cormack et al.[6] For $(n, \alpha)$ collisions, $d\sigma/d\Omega$ was taken equal to $K\exp(-5.0\theta^2)$ after Tannenwald.[7] The methods employed to correlate the above distributions with our uniform distribution of random numbers $0 \leq N \leq 1$ are described in reference 1 and by Gradsztajn.[8]

The potential square well is taken as in reference 3. The nucleons have a Fermi momentum distribution, whereas the $\alpha$ clusters are all considered as having an energy $E_0 = 5$ MeV. The binding energies taken for nucleons and $\alpha$ clusters are, respectively, 10 MeV and 7 MeV; and Coulomb barrier values are 3.5 MeV and 7 MeV, respectively.

In the present calculations we have postulated that an $\alpha$ cluster has only two possibilities after being knocked on: It can be emitted out of the nucleus if its kinetic energy is greater than the sum of its binding energy, Coulomb energy, and $E_0$. If not, it is absorbed but cannot cause other collisions.

All geometrical cross sections are calculated on the basis of $r_0 = 1.3$ fermis. The following results have been obtained:

(1) $C^{12}(p, p\alpha)Be^8$.—If $P = 40\%$, the calculated cross section is 37 mb for an incident proton energy of 156 MeV. The experimental value given by Samman and Cüer[9] is 33 mb for 180-MeV protons and 22 mb for 340-MeV protons. The excitation energy distribution is not incompatible with the values given in reference 9.

(2) $C^{12}(p, 3pxn)Be$.—Our results are compared with the experimental ones of Yuasa, Bowden, and Bowman, which give $\sigma \simeq 4$ mb for a proton energy of 110-135 MeV.[10] The calculated cross sections with $P = 40\%$ and $P = 0\%$ are, respectively, for 156-MeV protons, 2.4 mb and 8.4 mb; for 135 MeV, 1.9 mb and 5.8 mb. The number of calculated events lies between 5000 and 9000. In Fig. 1 the number of events is plotted against $\Delta E = E^* + (n-1)B$, where $E^*$ is the excitation energy of the residual nucleus, $B$ the binding energy, and $n$ the number of outgoing particles.

(3) $C^{12}(p, 2pxn)B$.—The experimental cross section, taken from Yuasa and Poulet[11] for 110-MeV protons, is $29 \pm 5$ mb. The calculated cross sections are the following (in mb), $E_p$ being the energy of the incoming proton:

| $E_p$ (MeV) \ $P$ | 40% | 30% | 0% |
|---|---|---|---|
| 156 | 28 | ... | 57 |
| 110 | 20 | 25 | 41 |

The $\Delta E$ spectrum is shown in Fig. 2.

(4) Total inelastic cross section.—On $C^{12}$, calculations on 1000 events lead, as expected, to the same results ($\sigma = 180$ mb) regardless of $P$ values, in agreement with the experimental value of Muirhead and Rosser[12]: $210 \pm 30$ mb for 140-MeV protons.

The above calculations show that the Monte Carlo method applied for intranuclear cascade in light nuclei can give a good agreement with ex-

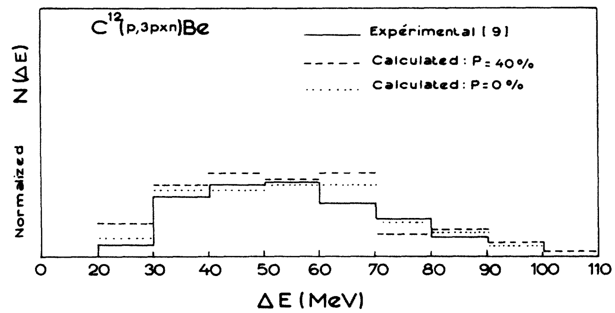


FIG. 1. Number of $(p, 3pxn)$ events against $\Delta E = E^* + (n-1)B$.

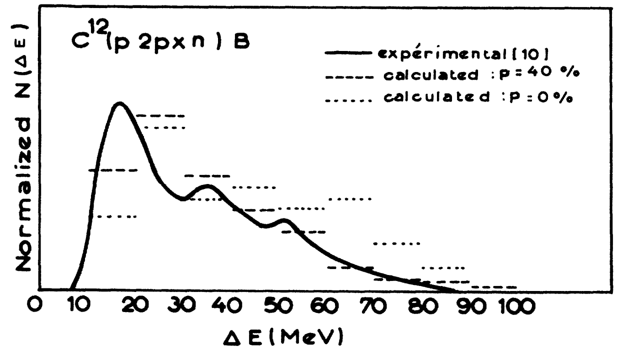


FIG. 2. Number of $(p, 2pxn)$ events against $\Delta E = E^* + (n-1)B$.

periment.

The calculations of $(p,p\alpha)$, $(p,2pxn)$ and $(p,3pxn)$ cascades, taking into account the $p$-$\alpha$ collisions, give good values for the cross sections and $\Delta E$ spectra, but results still compatible with experiment can be obtained with $P = 0\%$ for the last two.

Other Monte Carlo calculations are in progress for several other light nuclei and various reactions.

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[1]E. Abate, G. Bellini, E. Fiorini, and S. Ratti, Nuovo Cimento 22, 1206 (1961).
[2]H. W. Bertini, Phys. Rev. 131, 1801 (1963).
[3]E. Gradsztajn, J. Phys. Radium 24, 829 (1963).
[4]N. Metropolis et al., Phys. Rev. 110, 185 (1958).
[5]W. Selove and J. M. Teem, Phys. Rev. 112, 1658 (1958).
[6]A. M. Cormack, J. N. Palmieri, N. F. Ramsey, and Richard Wilson, Phys. Rev. 115, 599 (1959).
[7]P. E. Tannenwald, Phys. Rev. 89, 508 (1953).
[8]E. Gradsztajn, Laboratoire Joliot-Curie-Orsay Report No. E64.14 (unpublished).
[9]A. Samman and P. J. Cuer, J. Phys. Radium 19, 13 (1958).
[10]T. Yuasa, A. R. Bowden, and M. R. Bowman, private communication.
[11]T. Yuasa and M. Poulet, J. Phys. Radium 24, 1062 (1963).
[12]H. Muirhead and W. G. V. Rosser, Phil. Mag. 46, 652 (1955).

## LIFETIMES OF $d_{3/2}$ HOLE STATES IN SCANDIUM ISOTOPES*

R. E. Holland, F. J. Lynch, and K.-E. Nystén†
Argonne National Laboratory, Argonne, Illinois
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The location of $d_{3/2}$ hole states in the odd-$A$ isotopes of scandium has been inferred from the angular distributions of pickup reactions by Yntema and Satchler.[1] They observed such states in $Sc^{45}$, $Sc^{47}$, and $Sc^{49}$, and on this basis French[2] predicted that such a $d_{3/2}$ "hole" state (formed by promoting a $d_{3/2}$ proton to the $f_{7/2}$ shell) should also occur in $Sc^{43}$ near the ground state. We therefore concluded that the first excited state of $Sc^{43}$, which we had previously shown to be metastable with a lifetime 190 times the single-particle estimate for an $M2$ transition,[3] is the predicted $d_{3/2}$ "hole" state and that the transition is $M2$. The "hole" level in $Sc^{45}$ was observed by Yntema and Erskine[4] with the reaction $Ti^{48}(p,\alpha)Sc^{45}$ and the excitation energy was found to be 13 keV. In $Sc^{47}$, Yntema and Satchler[1] found the hole state at about 800-keV excitation with the reaction $Ti^{48}(d, He^3)Sc^{47}$; and in $Sc^{49}$, which we have not investigated, they found the hole state at 2.4 MeV.

We have now observed the gamma rays (which were not previously seen) from these levels in $Sc^{43}$, $Sc^{45}$, and $Sc^{47}$ and measured their lifetimes. Our results show that the first excited states of all three isotopes are indeed metastable (corresponding to $M2$ transitions) so they may be explained as $d_{3/2}$ hole states formed by promoting a $d_{3/2}$ proton to the $f_{7/2}$ shell. The level diagrams for these nuclei are given in Fig. 1.