CERN-TH.5040/88

RATES FOR INELASTIC NUCLEAR EXCITATION BY DARK MATTER PARTICLES

John Ellis and R.A. Flores^{*)}

CERN - Geneva

and

J.D. Lewin
Rutherford-Appleton Laboratory
Chilton, U.K.

ABSTRACT

We calculate rates for the inelastic scattering of dark matter particles X on nuclei to produce low-lying excited nuclear states. Assuming a Maxwellian velocity distribution for the dark matter particles X , the inelastic two-body phase space suppresses all rates by factors >10 for $m_X < 100$ GeV unless the excitation energy $\Delta E < 100$ keV. We catalogue all stable nuclei with excited states in this range, and we estimate inelastic scattering matrix elements by relating them to M1 transitions, after correcting for internal conversions. Our calculated rates are typically $< 10^{-4}$ events/kg.day, with the least unfavourable rates being for $^{169}_{69}\text{Tm}$ and $^{187}_{75}\text{Os}$. Problems of natural radioactivity and expense disfavour these and many other materials, leaving $^{127}_{53}\text{I}$, $^{183}_{74}\text{W}$ and $^{201}_{80}\text{Hg}$ as the least unpromising isotopes.

^{*)}Address after September 1, 1988: School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455.

There is considerable astrophysical evidence that galactic discs are embedded in haloes of dark matter [1] which is unlikely to be baryonic [2]. Theoretical physicists are challenged to devise particle candidates for this dark matter, and experimentalists are challenged to test them. Among the favoured particle candidates are various massive, electrically neutral, weakly interacting particles such as the photinos and higgsinos present in supersymmetric theories [3]. The most satisfying tests of such theoretical models are direct searches in the laboratory. Two techniques have been proposed [4] for the laboratory detection of massive dark matter particles X . One is to search for elastic X -nucleus scattering, as manifested by nuclear recoil energy in the keV range. The other is to search for inelastic X -nucleus scattering which produces a low-lying excited nuclear state [4,5].

This process has the double signature of recoil energy followed ~ 1 ns later by the emission of a decay photon with energy in the range $\sim (10 \text{ to } 100)$ keV. The double signature can be used to suppress backgrounds. It might enable dark matter searches to be carried out at higher temperatures and/or in larger blocks of material than those needed for elastic scattering experiments. On the other hand, the rates for the excitations of individual inelastic channels are likely to be suppressed relative to elastic scattering rates by phase space effects and/or smaller wave function overlaps. There are many calculations of elastic X -nucleon scattering rates [6,7]. However, we know of no previous complete calculations of inelastic excitation rates.

In this paper we present first evaluations of the rates for inelastic excitations by heavy Majorana fermions such as photinos or higgsinos. We calculate inelastic two-body phase space suppression factors as functions of the nuclear mass and excitation energy, assuming a Maxwellian distribution for the velocities of the dark matter particles (see, e.g., Ref. [6]). Since phase space suppresses rates by factors > 10 for all particles X weighing less than 100 GeV if the excitation energy $\Delta E > 100$ keV, we only examine stable nuclei with excited states: $\Delta E < 100$ keV [8]. All these are even-odd or odd-even isotopes. We estimate inelastic scattering matrix elements in the context of the nuclear shell model, which relates them to M1 transition matrix elements. The relationship is a simple dark matter particle-dependent factor for even-odd nuclei, for which the nucleon orbital angular momentum makes no contribution to the M1 matrix element, but is more indirect for odd-even nuclei, which have a proton orbital angular momentum contribution. The M1 transition matrix elements are extracted from the experimental lifetimes of the

excited states [8,9], after correcting for internal conversions^{*)}. The resulting rates are shown in the Table. Because the magnetic transition matrix elements are smaller than the proton and neutron magnetic moments, the inelastic scattering rates are discouragingly small, the most favourable cases being $^{169}_{69}\text{Tm}$ and $^{187}_{76}\text{Os}$ with rates $\lesssim 10^{-3}/\text{kg}\cdot\text{day}$ for $m_{\chi} \sim (20 \text{ to } 100) \text{ GeV}$, other rates being $\sim 10^{-4}/\text{kg}\cdot\text{day}$ or smaller. The least unpromising materials from the points of view of natural radioactivity and expense seem to be $^{127}_{53}\text{I}$, $^{183}_{74}\text{W}$ and $^{201}_{80}\text{Hg}$. Despite the smallness of these rates, we believe that experimentalists' interest and ingenuity justifies putting them on record.

The central formula for the rate of inelastic scattering of dark matter particles on matter, assuming an isotropic differential cross-section, is

$$R_I = \frac{m_X m_N}{\pi (m_X + m_N)^2} \cdot \rho_X \langle |\underline{u} - \underline{v}_0| \rangle f |\langle N^* | \eta | N \rangle|^2 \quad (1)$$

where $m_X(m_N)$ is the relic (nucleus) mass, ρ_X is the local density of halo particles expected [10] to be $\sim 0.3 \text{ GeVcm}^{-3}$, and $\langle |\underline{u} - \underline{v}_0| \rangle$ is the mean velocity of the halo particles in the Earth's rest frame. Finally, f is a phase space suppression factor and $\langle N^* | \eta | N \rangle$ an inelastic matrix element, that we now discuss in more detail.

Assuming that $\langle N^* | \eta | N \rangle$ is independent of velocity, the phase space ratio f is given by

$$f = \langle \left| \frac{p_f}{p_i} \right|_{\text{CM}} |\underline{u} - \underline{v}_0| \rangle / \langle |\underline{u} - \underline{v}_0| \rangle \quad (2)$$

where $p_f(p_i)$ is the final (initial) momentum of the dark matter particle X in the centre-of-mass frame CM, $\underline{v}_0 \sim 220 \text{ kms}^{-1}$ is the galactic orbital velocity of the Sun, and $\underline{u}$ is the velocity of X in the rest frame of the Galaxy. The averages in (1) and (2) are over the distribution of this velocity, which we assume [6] to be Maxwellian with a cut-off at the local escape velocity from the halo, $v_{\text{esc}} \sim 600 \text{ kms}^{-1}$. In the case of elastic scattering, $\Delta E = 0$ and $|p_f/p_i| = 1$, so that $f(\Delta E = 0) = 1$. On the other hand, in order to excite the transition, it is necessary that $|\underline{u} - \underline{v}_0|^2 > 2\Delta E(1 + m_X/m_N)/m_X$. Hence $f = 0$ for $m_X \leq 25 \text{ GeV}$ if, for example, $\Delta E = 100 \text{ keV}$. The figure shows f as a function of m_X for three values of ΔE and two choices of the atomic number A . We see that $f < 0.1$ for all $m_X \leq 100 \text{ GeV}$ and $A \leq 200$ unless $\Delta E \leq 100 \text{ keV}$. For larger excitation energies, inelastic rates would be suppressed by more than a factor of 10 relative to elastic

^{*)} We have not been able to do this for the 1.56 keV excited state of $^{201}_{80}\text{Hg}$ because the needed data are not available [8,9]. This is unfortunate, because its low excitation energy makes this state very interesting.

rates, which are $\lesssim 1 \text{ kg}^{-1} \text{d}^{-1}$ for particles with spin-dependent interactions such as a generic supersymmetric neutralino. Therefore, we only consider isotopes with excited states at energies $\Delta E \leq 100 \text{ keV}$.

We have searched through the 7th edition of the Table of isotopes [8] for all isotopes satisfying the following criteria:

- (1) They should have an excited state with $\Delta E \leq 100 \text{ keV}$.
- (2) The ground state should be stable, primarily so as to avoid large radioactive backgrounds^{*)}.
- (3) The de-excitation should be predominantly an M1 transition, whose rate can be used to estimate the excitation matrix element.

We have found the isotopes listed in the Table, many of whose natural abundances are not very large. Note that in addition $^{201}_{80}\text{Hg}$ has an excited state with $\Delta E = 1.56 \text{ keV}$. Unfortunately, the data which would be needed to evaluate its transition matrix element appear to be unavailable [8,9].

We now discuss the evaluation of the transition matrix element $\langle N^* | \eta | N \rangle$ in Eq. (1). For particles with spin-dependent interactions such as Majorana fermions including the photino and higgsino, the operator $\eta \propto \underline{S}_X \cdot \underline{S}_q$ where $\underline{S}_{X(q)}$ is the relic (quark) spin operator [6,7]. Hence we need to evaluate the inelastic matrix element $\langle N^* | \underline{S}_q | N \rangle$ of the quark spin operator, for which we use the nuclear shell model [11]. In this model, the protons and neutrons separately fill up energy shells in pairs of opposite spin. Therefore, unpaired odd nucleons contribute to $\langle N^* | \underline{S}_q | N \rangle$ and hence to $\langle N^* | \eta | N \rangle$. Assuming, as in this shell model, that each nucleon retains its identity in the nucleus, the first step is to evaluate the proton or neutron matrix element

$$\langle p(n) | 2\underline{S}_q | p(n) \rangle = \langle p(n) | \bar{q} \gamma_\mu \gamma_5 q | p(n) \rangle = 2\Delta q \underline{S}_{p(n)} \quad (3)$$

where Δq is the mean fraction of the nucleon spin contributed by quarks (and anti-quarks) of flavour q .

It is not yet possible to compute the Δq 's from first principles, so we must use data. Until recently, the only two relevant data were from neutron and hyperon β -decay, and they could be used to extract the three required Δq ($q = u, d, s$) only if one made the supplementary assumption that $\Delta s = 0$, as expected in the naive non-relativistic quark model (NQM) or more generally if only valence quarks contributed

^{*)} In certain cases these might be manageable, but large enough pure amounts of the unstable isotope are unlikely to be available.

to the nucleon spin [12]. However, recent polarized μp scattering data from the EMC [13] have cast doubt on this simple assumption. These data can be interpreted [14,15] if the strange sea has a net negative polarization $\Delta s < 0$, and the total net contribution of u,d and s quarks to the proton spin is small:

$$\Delta u = 0.74 \pm 0.08, \Delta d = -0.51 \pm 0.08, \Delta s = -0.23 \pm 0.08 \quad (4)$$

$$\Delta u + \Delta d + \Delta s = 0.00 \pm 0.24$$

Experimental support for this a priori striking conclusion is provided [16] by recent elastic νp and $\bar{\nu} p$ scattering data [17], which indicate that the Z^0 has a non-zero axial current coupling to s quarks in the proton. Moreover, a possible theoretical explanation [18] of the EMC result (4) has been provided a posteriori in the context of the Skyrme model. Therefore, the calculations we tabulate are made using the central values (4) of the Δq 's implied by the EMC data. However, we also list in the table caption the factors by which the rates would be multiplied if one used the NQM values $\Delta u = 0.97$, $\Delta d = -0.28$, $\Delta s = 0$.

After evaluating $\langle p(n) | \underline{S}_q | p(n) \rangle = \Delta q \cdot \underline{S}_{p(n)}$, the next step is to evaluate $\langle N^* | \underline{S}_{p(n)} | N \rangle$, for which we use the available data on M1 magnetic dipole transmissions [8,9]. The width for a de-excitation M1 transition $N^* \rightarrow N\gamma$ is

$$\Gamma_{M1} = \frac{\alpha_{em}}{3} \cdot \frac{E_\gamma^3}{m^2} |M_{M1}|^2 \quad (5)$$

where m is the nucleon mass, α_{em} is the fine structure constant and $E_\gamma = \Delta E$ is the energy of the emitted photon. The matrix element M_{M1} is in turn given by

$$M_{M1} = \sum_p \langle N^* | L_z | N \rangle + \sum_{p,n} \mu_{p,n} \langle N^* | \sigma_z | N \rangle \quad (6)$$

where $\mu_p = 2.79$ ($\mu_n = -1.91$) is the anomalous magnetic moment of the proton (neutron) in Bohr magnetons, and L_z ($\sigma_z = 2S_z$) is the third component of orbital (spin) angular momentum. To extract M_{M1} from the lifetime τ of the excited state, we need to make the appropriate correction for internal conversion Γ_e :

$$\tau^{-1} = \Gamma_{M1} + \Gamma_e \equiv (1 + \alpha) \Gamma_{M1} \quad (7)$$

where the internal conversion factor α is experimentally measurable. Wherever possible, we have obtained the values of α from the Nuclear Data Sheets [9]. In some cases, α is only available from theoretical interpolation and we have used the values tabulated in Ref. [19]. [Note that neither τ nor α is available for the 1.56 keV level of $^{201}_{80}\text{Hg}$ mentioned earlier, nor indeed is it even known to decay via an M1 transition.] The values of $|M_{M1}|^2$ listed in the Table span the ranges

allowed by published data on τ : the subsequent interaction rates are calculated using the central values of $|M_{M1}|^2$.

We see from Eq. (6) that for a nucleus with an unpaired neutron

$$M_{M1} = 2\mu_n \langle N^* | S_z | N \rangle = 2\mu_n O_* J_z \quad (8)$$

where O_* is an inelastic wave-function overlap factor which can now be determined from the data. However, some of our isotopes have an unpaired proton, in which case the relation (8) between M_{M1} and S_z is modified by the orbital angular momentum contribution (6). This modification can in principle be computed in the shell model, but is typically smaller than the likely error in the model prediction inferred from the measured magnetic moments. For definiteness, in these cases we also use the relation (8) with μ_n replaced by μ_p , but caveat emptor. We can now combine all the factors to evaluate inelastic interaction rates (1). For concreteness, we first take the dark matter particle X to be a pure photino state $\tilde{\gamma}$, for which

$$\eta = \sum_q \frac{4e^2 Q_q^2}{m_{\tilde{q}}^2} S_{\tilde{\gamma}} \cdot S_q \quad (9)$$

We assume that all the squark masses $m_{\tilde{q}}$ are equal. The inelastic scattering rate (1) is then:

$$R_I = \frac{3.6 \text{ events}}{\text{kg} \cdot \text{day}} \left(\frac{\rho_X}{0.3 \text{ GeV cm}^{-3}} \right) \left(\frac{\langle |u-v| \rangle}{320 \text{ km s}^{-1}} \right) \left| \frac{M_{M1}}{\mu_{p,n}} \right|^2 \cdot \frac{2J^*+1}{2J+1} \cdot F_{p,n} \cdot K \left(\frac{100 \text{ GeV}}{m_{\tilde{q}}} \right)^4 \quad (10)$$

where

$$F_{p,n} = \left(\sum_q Q_q^2 \Delta q \right)^2 \quad (11)$$

which take the values $F_p = 0.061$, $F_n = 0.029$ when we use the central EMC estimates (4) of the Δq , and

$$K = f \cdot \frac{4m_{\tilde{\gamma}} m_N}{(m_{\tilde{\gamma}} + m_N)^2} \quad (12)$$

is a kinematic factor which is always ≤ 1 . The common value of $m_{\tilde{q}}$ for any given value of $m_{\tilde{\gamma}}$ can be fixed by requiring that the present cosmological density of relic photinos is the critical density: $\Omega_{\tilde{\gamma}} = 1$ for a present Hubble expansion velocity of $50 \text{ km s}^{-1} \text{ Mpc}^{-1}$. If slepton and squark masses are equal, this condition requires [20]

$$m_{\tilde{q}} \simeq 57 \text{ GeV} \cdot \left(1 + 0.04 \left(\frac{m_{\tilde{\chi}}}{\text{GeV}}\right)^2\right)^{1/4} \quad (13a)$$

whereas if supergravity relations between $m_{\tilde{\chi}}$, $m_{\tilde{q}}$ and $m_{\tilde{\gamma}}$ are used we find [21]

$$m_{\tilde{q}} \simeq 44 \text{ GeV} + 5.5 \left(\frac{m_{\tilde{\chi}}}{\text{GeV}}\right) \quad (13b)$$

We use the relation (13a) for $m_{\tilde{q}}$ to obtain the tabulated numerical values of the rates. Those for other values of $m_{\tilde{q}}$ can be obtained by rescaling: $R'_I = R_I \times [m_{\tilde{q}}(13a)/m_{\tilde{q}}]^4$.

The rates obtained using the EMC values of $F_{p,n}$ and $m_{\tilde{q}}$ from (13a) are shown in the Table. They are small in the first place because the kinematic factor f entails a big suppression in general unless $m_{\tilde{\gamma}} \gtrsim 20 \text{ GeV}$, in which case the elastic scattering rates were already $\ll 0.1 \text{ events kg}^{-1}\text{d}^{-1}$ [7]. Secondly, the inferred values of $|M_{M1}|^2$ are typically one or two orders of magnitude smaller than $\mu_{p,n}^2$, expressing the fact that inelastic overlap factors O_* (8) are usually small. We note in particular that in the a priori favourable cases with $\Delta E < 15 \text{ keV}$ ($^{57}_{26}\text{Fe}$, $^{83}_{36}\text{Kr}$, $^{169}_{69}\text{Tm}$, $^{187}_{76}\text{Os}$) either τ is long ($^{57}_{26}\text{Fe}$, $^{83}_{36}\text{Kr}$) or α is large ($^{169}_{69}\text{Tm}$, $^{187}_{76}\text{Os}$), so that $|M_{M1}|^2$ is not cooperatively large. Note that we have not included the isotopic abundance factors, and that the natural abundances of the isotopes considered here may be as small as $\sim 1\%$.

The Table can also be used to infer inelastic interaction rates for higgsinos $\tilde{h}$. In this case the hadronic matrix elements of the interaction operator in (1) are proportional to $\sum_q T_3 \Delta q$, and the coefficient depends on the a priori unknown ratio of two Higgs v.e.v.'s, which is chosen: $\Omega_{\tilde{h}} = 1$ [14]. The calculations of the inelastic interaction rates proceeds much as in the $\tilde{\gamma}$ case, and the results are broadly similar in magnitude. As in the case of the $\tilde{\gamma}$ rates, we use the EMC central values (4) for the Δq , and the table caption lists the correction factors to be applied to the entries in the Table to convert from $\tilde{\gamma}$ -nucleus to $\tilde{h}$ -nucleus scattering for $m_{\tilde{h}} = 10$ and 20 GeV . Rates for $m_{\tilde{h}} > 20 \text{ GeV}$ are smaller and highly mass-dependent when $m_{\tilde{h}} \sim m_{Z^0}/2$, if one adjusts the Higgs v.e.v. ratio to get $\Omega_{\tilde{h}} = 1$ as done here.

We conclude that inelastic scattering rates for dark matter particles X with spin-dependent interactions are small. In the particular case when X is a photino $\tilde{\gamma}$, $R_I \lesssim 10^{-3} \text{ kg}^{-1}\text{d}^{-1}$, with the most favourable rates occurring for the isotopes $^{169}_{69}\text{Tm}$ and $^{187}_{76}\text{Os}$. Inelastic scattering has the double signature of recoil energy accompanied by a delayed γ -ray. The natural width and the Dppler broadening of this line would be negligible. The dominant contribution to its apparent width

would be the instrumental resolution. Many of the elements considered have other isotopes which are radioactive, which give rise to severe backgrounds within the experimental energy resolution. Moreover, many of the elements considered should be regarded as toxic. If this were not enough already, many of them are expensive [22]. The least unpromising materials from the points of view of natural radio activity and expense are $^{127}_{53}\text{I}$, $^{183}_{74}\text{W}$ and $^{201}_{80}\text{Hg}$, which could give event rates between 10^{-5} and $10^{-4} \text{ kg}^{-1}\text{day}^{-1}$. We do not address here the question whether these are feasible detector materials. It remains to be seen whether one can build a detector large enough ($\sim 1\text{t}$) to exploit the double signature of recoil energy and a monochromatic decay photon.

ACKNOWLEDGEMENTS

We thank A. Drukier, T.E.O. Ericson, L. Gonzalez-Mestres and especially P.F. Smith for useful conversations.

TABLE CAPTION

Rates for inelastic $\tilde{\gamma}$ -N scattering calculated assuming central EMC values (4) for the spin content of the nucleon and m_q chosen as in (13a) to obtain $\Omega_{\tilde{\gamma}} = 1$. Rates calculated using the NQM values of the Δq would be larger by a factor ~ 2.6 for isotopes with an odd proton ($^{121}_{51}\text{Sb}$, $^{151}_{63}\text{Eu}$, $^{169}_{69}\text{Tm}$), and smaller by a factor ~ 100 for all the other isotopes, which each have an odd neutron. Rates for inelastic $\tilde{h}$ -N scattering when $m_h = 10(20)$ GeV are larger by a factor $\sim 4.4(\sim 3.3)$ for both even-odd and odd-even nuclei.

Isotope	J ^P N N [*]	Natural abundance %	Excitation Energy ΔE (keV)	Half-life τ (ns)	Internal conver- sion correction α	NDS vol.pg.(yr)	$ M_{M1} ^2$	Inelastic Scatt. Rate $R_I (10^6 \text{ kg.day})^{-1}$ for m_γ (GeV)			
								10	20	50	100
$^{121}_{51}\text{Sb}$	$5/2^+ (7/2)^+$	57.3	37.1	3.0-3.5	11.1	<u>26,434</u> (79)	0.09-0.08	—	0.22	0.50	0.27
$^{127}_{53}\text{I}$	$5/2^+ 7/2^+$	100	57.6	1.9	3.8	<u>35,242</u> (82)	0.10	—	0.012	0.20	0.17
$^{133}_{55}\text{Cs}$	$7/2^+ 5/2^+$	100	81.0	6.3	1.6	<u>49,692</u> (86)	0.02	—	—	0.0060	0.0092
$^{151}_{63}\text{Eu}$	$5/2^+ 7/2^+$	47.9	21.5	8.8-9.5	28.6	<u>19,79</u> (76)	0.06	0.20	0.89	0.74	0.32
$^{159}_{65}\text{Tb}$	$3/2^+ 5/2^+$	100	58.0	0.06-0.13	11 [*]	<u>27,191</u> (78)	1.2-0.5	—	0.11	1.9	1.7
$^{165}_{67}\text{Ho}$	$7/2^- 9/2^-$	100	94.7	0.022	3.1	<u>50,176</u> (87)	2.2	—	—	0.61	1.4
$^{169}_{69}\text{Tm}$	$1/2^+ 3/2^+$	100	8.4	3.5-4.0	220-325	<u>36,487</u> (82)	0.36-0.21	17.5	18.4	7.6	2.7
$^{191}_{77}\text{Ir}$	$3/2^+ 1/2^+$	37.3	82.4	4.0	10.9	<u>30,682</u> (80)	0.004(c)	—	—	—	0.0015
$^{193}_{77}\text{Ir}$	$3/2^+ 1/2^+$	62.7	73.0	6.1-6.3	6.8	<u>32,619</u> (81)	0.006(c)	—	—	0.0024	0.0032
$^{197}_{79}\text{Au}$	$3/2^+ 1/2^+$	100	77.3	1.9	4.2	<u>34,133</u> (81)	0.04(c)	—	—	0.012	0.017

* interpolated [19] taking $\alpha = \alpha_K + \alpha_L + (4/3)\alpha_M$

(c) corrected for significant E2 component

— rate $< 10^{-7}$ /kg.day

(a) Rates for isotopes with odd protons

Isotope	J^P N N [*]	Natural abundance %	Excitation Energy ΔE (keV)	Half-life τ (ns)	Internal conver- sion correction α	NDS vol.pg.(yr)	$ M_{M1} ^2$	Inelastic Scatt. Rate R_I (10^4 kg.day) ⁻¹ for m_γ (GeV)			
								10	20	50	100
⁵⁷ ₂₆ Fe	1/2 ⁻ 3/2 ⁻	2.15	14.4	97.7-98.1	8.2	47, 54(86)	0.06	2.2	3.7	1.5	0.42
⁶¹ ₂₈ Ni	3/2 ⁻ 5/2 ⁻	1.13	67.4	5.1-5.3	0.14	38,496(83)	0.09	—	—	0.040	0.039
⁸³ ₃₆ Kr	9/2 ⁺ 7/2 ⁺	11.5	9.4	147	17.1	49,610(86)	0.08	2.7	2.8	0.99	0.29
¹¹⁹ ₅₀ Sn	1/2 ⁺ 3/2 ⁺	8.6	23.9	17.8-18.1	5.2	26,247(79)	0.11	0.33	2.1	1.9	0.77
¹²⁵ ₅₂ Te	1/2 ⁺ 3/2 ⁺	7.0	35.5	1.48-1.54	14.0	32,542(81)	0.17-0.16	0.0081	0.79	1.6	0.86
¹²⁹ ₅₄ Xe	1/2 ⁺ 3/2 ⁺	26.4	39.6	1.0	12.3	39,608(83)	0.20	—	0.58	1.7	0.95
¹³¹ ₅₄ Xe	3/2 ⁺ 1/2 ⁺	21.2	80.2	0.49	1.6	17,598(76)	0.25	—	—	0.056	0.084
¹⁴⁵ ₆₀ Nd	7/2 ⁻ 5/2 ⁻	8.3	72.5	0.72	3.6	49, 31(86)	0.13	—	—	0.074	0.093
¹⁴⁹ ₆₂ Sm	7/2 ⁻ 5/2 ⁻	13.9	22.5	7.1-7.6	30.0	46,103(85)	0.07-0.06	0.092	0.48	0.42	0.18
¹⁵⁵ ₆₄ Gd	3/2 ⁻ 5/2 ⁻	14.8	60.0	0.19	9.4	50,608(87)	0.39	—	0.041	0.89	0.83
¹⁵⁷ ₆₄ Gd	3/2 ⁻ 5/2 ⁻	15.7	54.5	0.13	12.4	39,132(83)	0.59	—	0.16	1.8	1.5
¹⁶¹ ₆₆ Dy	5/2 ⁺ 7/2 ⁺	19.0	43.8	0.78-0.92	6.1	43, 61(84)	0.30-0.35	—	0.37	1.5	0.99
¹⁶⁷ ₆₈ Er	7/2 ⁺ 9/2 ⁺	22.9	79.3	0.12	5.7	17,161(76)	0.41	—	—	0.29	0.44
¹⁷¹ ₇₀ Yb	1/2 ⁻ 3/2 ⁻	14.4	66.7	0.81	13.0	43,180(84)	0.03 ^(c)	—	0.0011	0.067	0.075
¹⁷³ ₇₀ Yb	5/2 ⁻ 7/2 ⁻	16.2	78.6	0.038-0.052	7.0	14,328(75)	1.1-0.8	—	—	0.75	1.1
¹⁸³ ₇₄ W	1/2 ⁻ 3/2 ⁻	14.3	46.5	0.18	8.6	16,292(75)	1.0	—	1.1	5.7	4.1
¹⁸⁷ ₇₆ Os	1/2 ⁻ 3/2 ⁻	1.6	9.8	2.4	220 [*]	14,370(75)	0.33	15.6	18.9	8.6	3.2
¹⁸⁹ ₇₆ Os	3/2 ⁻ 1/2 ⁻	16.1	36.2	0.53	21.1	34,570(81)	0.30	0.0030	0.30	0.71	0.42
¹⁹⁵ ₇₈ Pt	1/2 ⁻ 3/2 ⁻	33.8	98.9	0.16	7.1	23,631(78)	0.13	—	—	0.054	0.14
²⁰¹ ₈₀ Hg	3/2 ⁻ (3/2) ⁻	13.2	32.2	0.1-0.2	42	49,753(86)	0.53-0.27 ^s	0.039	1.1	2.0	1.1

from Nucl. Phys. A166 (1971) 573

c) corrected for significant E2 component

corrected for decay via E = 1.56 keV level

— rate <10⁻⁷/kg.day

(b) Rates for isotopes with odd neutrons

REFERENCES

- [1] For a recent review, see, e.g.:
V. Trimble, Ann. Rev. Astron. Astrophys. 25 (1987) 425.
- [2] See, e.g.:
D. Hegyi and K. Olive, Ap. J. 303 (1986) 56.
- [3] H. Goldberg, Phys. Rev. Lett. 50 (1983) 1419;
J. Ellis, J.S. Hagelin, D.V. Nanopoulos, K. Olive and M. Srednicki, Nucl. Phys. B238 (1984) 453;
L. Ibáñez, Phys. Lett. 137B (1984) 160;
J.S. Hagelin, G. Kane and S. Raby, Nucl. Phys. B241 (1984) 638.
- [4] M.W. Goodman and E. Witten, Phys. Rev. D31 (1985) 3059.
- [5] L. Gonzalez-Mestres and Perret-Gallix, preprint LAPP-EXP-87-03 (1987).
- [6] For a review, see, e.g.:
J.R. Primack, D. Seckel and B. Sadoulet, U.C. Santa Cruz preprint SCIPP 88/14 (1988).
- [7] J. Ellis and R. Flores, CERN preprint TH.4911/87 (1987).
- [8] C.M. Lederer and V.S. Shirley, eds., "Table of Isotopes", (Wiley, N.Y., 1978).
- [9] J.K. Tuli, ed., "Nuclear Data Sheets", (Academic Press, Duluth, Minnesota); see Table for specific references.
- [10] R.A. Flores, CERN preprint TH.4736/87 (1987).
- [11] See, e.g.:
P. Mermier and E. Sheldon, "Physics of Nuclei and Particles", (Academic Press, N.Y., 1970).
- [12] J. Ellis and R. Jaffe, Phys. Rev. D9 (1974) 1444.
- [13] J. Ashman et al., CERN preprint CERN-EP/87-230 (1987).
- [14] J. Ellis, R. Flores and S. Ritz, Phys. Lett. 198B (1987) 393.
- [15] M. Glück and E. Reya, Dortmund preprint DO-TH-87/14, (August 1987).
- [16] J. Ellis and M. Karliner, SLAC preprint PUB-4592 (1988).
- [17] L. Ahrens et al., Phys. Rev. D35 (1987) 785.
- [18] S. Brodsky, J. Ellis and M. Karliner, SLAC preprint PUB-4519 (1988).
- [19] R.S. Hager and E.C. Seltzer, Nuclear Data A4 (1968) 1.
- [20] M. Srednicki, K.A. Olive and J. Silk, Nucl. Phys. B279 (1987) 804.
- [21] J. Ellis, J.S. Hagelin and D.V. Nanopoulos, Phys. Lett. B158 (1985) 26.
- [22] Anything over US\$ 10^6 /ton; see R.C. Weast, ed., "Handbook of Chemistry and Physics", (CRC press, Boca Raton, Florida, 1987).

FIGURE CAPTION

The phase space suppression factor f for inelastic excitation [see Eq. (2)] computed as a function of m_X for different values of the excitation energy ΔE and the atomic number A of the target nucleus. The local escape velocity $v_{\text{esp}} = 580 \text{ kms}^{-1}$ here.